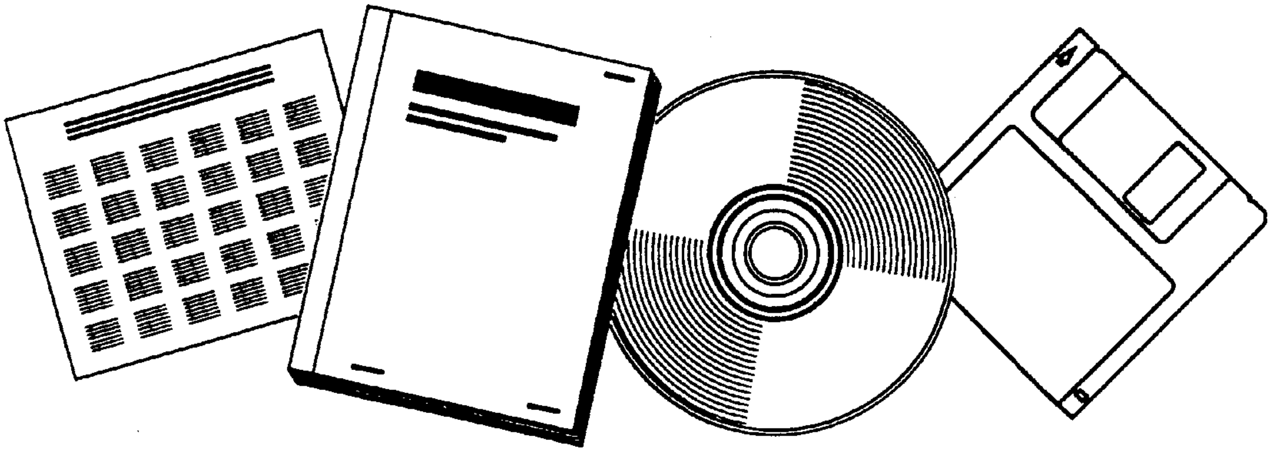
PB97-171888

INTERSECTION GEOMETRIC DESIGN AND OPERATIONAL GUIDELINES FOR OLDER DRIVERS AND PEDESTRIANS VOLUME I: FINAL REPORT

THE SCIENTEX CORPORATION
KULPSVILLE, PA

JUN 97



Intersection Geometric Design and Operational Guidelines for Older Drivers and Pedestrians

Volume I: Final Report

PUBLICATION NO. FHWA-RD-96-132

JUNE 1997

U.S. Department of Transportation
Federal Highway Administration

Research and Development
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

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

PB97-171888

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1. Report No. FHWA-RD-96-132	**3. Recipient's Catalog No.**
4. Title and Subtitle INTERSECTION GEOMETRIC DESIGN AND OPERATIONAL GUIDELINES FOR OLDER DRIVERS AND PEDESTRIANS, Volume I: Final Report	**5. Report Date** June 1997 **6. Performing Organization Code** 1433
7. Author(s) Loren Staplin, David L. Harkey, Kathy H. Lococo, and Mohammed S. Tarawneh	**8. Performing Organization Report No.** 1433/FR
9. Performing Organization Name and Address The Scientex Corporation Transportation Safety Division P.O. Box 1367, 1722 Sumneytown Pike Kulpsville, PA 19443	**10. Work Unit No. (TRAIS)** 3A6a-0022 **11. Contract or Grant No.** DTFH61-92-C-00142
12. Sponsoring Agency Name and Address Office of Safety and Traffic Operations R&D Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101-2296	**13. Type of Report and Period Covered** Final Report Oct. 1992 - July 1996 **14. Sponsoring Agency Code**

15. Supplementary Notes

Contracting Officer's Technical Representative: Elizabeth Alicandri, HSR-30

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

FHWA-RD-96-138 Volume II: Executive Summary
FHWA-RD-96-137 Volume III: Guidelines

17. Key Words Safety, Mobility, Age, Intersection, Design, Operations, Sight Distance, Channelization, Driver, Pedestrian, Critical Gap, Left-Turn Lane Offset	**18. Distribution Statement** No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified	Unclassified	249	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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.				
		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

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* 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

AARP	American Association of Retired Persons
AASHTO	American Association of State Highway and Transportation Officials
CRT	Cathode Ray Tube
DHV	Design Hour Volume
FHWA	Federal Highway Administration
GLM	General Linear Models (Statistical Analysis Procedure)
HTA	Hierarchical Task Analysis
IIHS	Insurance Institute for Highway Safety
ISD	Intersection Sight Distance
ITE	Institute of Transportation Engineers
LED	Light-Emitting Diode
MUTCD	*Manual on Uniform Traffic Control Devices*
NCHRP	National Cooperative Highway Research Program
OLTLG	Opposite Left-Turn Lane Geometry
PRT	Perception-Reaction Time
RT	Reaction Time
RTOR	Right Turn on Red
SAIC	Science Applications International Corporation
SAS	Statistical Analysis System
SD	Sight Distance
SSD	Stopping Sight Distance
TCD	Traffic Control Device
TRB	Transportation Research Board
TWLTL	Two-Way Left-Turn Lane
UFOV	Useful Field of View
WAIS-R	Wechsler Adult Intelligence Scale-Revised

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. In a recent analysis of nationwide accident data, the problems of older road users (age 64 or older) at intersections was summed up as follows:

- Thirty-three percent of the fatalities and 51 percent of the injuries experienced by older pedestrians occur at intersections.
- Thirty-seven percent of the fatalities and 60 percent of the injuries experienced by older drivers occur at intersections.

In both cases, these percentages exceeded those of other age groups, indicating the increased hazard for older road users at intersections (Hauer, 1988).

The fact that older drivers experience exaggerated difficulties with intersection use has been further documented in numerous recent accident analyses. There is evidence of an increase in multiple-vehicle intersection accident involvements for drivers over age 50, with a concurrent decrease in the percentage of single-vehicle accidents for this age group. 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). 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.

This report is divided into sections describing 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 in this area.

BACKGROUND INFORMATION

The literature search for this project began with the use of the DIALOG online information system, and included searches in TRIS, PsychINFO, NTIS, COMPENDEX PLUS, AGELINE, and FEDERAL RESEARCH IN PROGRESS. Other sources utilized in the acquisition and review of literature were unpublished articles and reports from TRB Committees, including those on Operational Effects of Geometrics (A3A08), Methodology for Evaluating Highway Improvements (A3A12), Geometric Design (A2A02), Vehicle User Characteristics (A3B02), Older Drivers (A3B13), and Pedestrians (A3B04). The following discussion presents an overview of older road user accident experiences at intersections; a description of older road user characteristics and perceived needs; and a review of the geometric design and operational standards employed at intersections.

ACCIDENT HISTORY

Older Drivers

Several studies have examined the types of accidents in which older drivers are over-involved and the types of maneuvers being performed just prior to the collision. 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 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 at unsignalized intersections showed older drivers **not** to be over-involved in left-turn accidents. 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).

Older Pedestrians

The analysis by Council and Zegeer (1992) included an examination of pedestrian accidents and the collision types in which older pedestrians were over-involved. The results showed older pedestrians to be 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 potential causes for this over-representation related to performance deficits may also be cited:

Left-Turn Accidents

- Increased exposure resulting from slower walking speed.
- Lack of understanding that vehicles may turn left during their WALK interval.
- Inadequate searching for left-turning vehicles before stepping into the street.
- Inability to react quickly enough to avoid a left-turning vehicle.
- Reduced peripheral vision.
- Too much reliance on the pedestrian signal alone.

Right-Turn Accidents

- Lack of understanding that vehicles may turn right during their WALK interval (either on green signal or right-turn-on-red).
- Lack of driver understanding that they must yield to pedestrians.
- Inadequate searching for right-turning vehicles before stepping into the street.
- Inability to react quickly enough to avoid a right-turning vehicle.
- Reduced peripheral vision.
- Too much reliance on the pedestrian signal alone.
- Large curb radii, resulting in high-speed turns and, ultimately, less reaction time.

CHARACTERISTICS OF OLDER ROAD USERS AFFECTING INTERSECTION USE

Older road users differ from their younger counterparts in a number of important ways, which in isolation and in combination may result in greater difficulties at intersections. The functional characteristics addressed in this review include capabilities and limitations pertinent to both *response initiation* and *movement execution* for older drivers and pedestrians alike. The findings of the literature review are summarized in terms of three broad categories of age-related diminished capabilities: (1) sensory/perceptual, (2) cognitive, and (3) physical/psychomotor.

Diminished Sensory/Perceptual Capabilities

The safety and mobility of older road users at intersections is overwhelmingly vision-dependent, thus changes in visual processes with normal aging dominated this section of the review. 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. Age differences in visual processes can best be understood by examining the physiological changes that are typically manifested in older adults and the consequent performance impairments that are most likely to impact the safe and effective use of intersections.

The largest single factor contributing to declining visual performance in the non-pathologic eye is increased light absorption and scattering in the lens due to its constant thickening and yellowing with age (Spector, 1982; Verriest, 1963). In addition, opacities in the form of cataracts may develop suddenly, causing significant back-reflection of light within the eye and a drastic reduction in the proportion of incident light reaching the retina. According to a recent review, however, there are not yet any reliable data describing systematic effects of different levels of severity of cataracts on driving performance (Klein, 1991). A distant second in importance to lens changes with age is deterioration in the structures of the retina and the neural pathway to the brain. All other factors, apart from pathology, may be grouped as minor in overall impact.

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, color vision, visual fields, dark adaptation and glare sensitivity, 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). The Framingham study (Kahn et al., 1977) reported that about 10 percent of men and women between ages 65 and 75 have acuity worse than 20/30, compared to roughly 30 percent over age 75. Dating at least back to Burg (1966), however, attempts to correlate declining static visual acuity with driving performance have shown only weak relationships. More recently, 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. Still, while acknowledging that a driver's response to intersection geometric features is influenced in part by the processing of high spatial frequency cues—for example, the characters on upstream advisory signs—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. Though the loss of sensory response is greatest for high-frequency (greater than 24 cycles/deg) information, older road users' sensitivity to visual contrast at lower and middle-range spatial frequencies (i.e., 6-, 12-, and 18-cycle/deg targets) also declines steadily with increasing age over 40 (Owsley, Sekuler, and Siemsen, 1983).

Performance deficits in color vision with increasing age—particularly a loss of blue-yellow discrimination—have been widely documented (Verriest, Van Laetham, and Uvijls, 1982). However, while certain treatments such as colored pavements could be considered as auxiliary cues to aid in the discrimination of raised surfaces, crosswalk areas, or other geometric features at intersections, color vision did not emerge as a principal concern in this study.

Age-related changes in visual fields can be measured either as a reduction in field area (contraction of the field limits) for different target sizes and intensities, or as an elevation in threshold values at distinct locations within the field limits. In general, field area declines as a function of decreasing target size and intensity. Decline in field area with age, for both central and peripheral isopters, has been demonstrated using kinetic testing methods[1] (Drance, Berry, and Hughes, 1967). Similarly, a steady rise as a function of age in the mean threshold for static fields of between 0.50 and 0.75 decibels per decade of age has been reported (Jaffe, Alvarado, and Juster, 1986). Large-scale accident analyses exploring the relationship between driving performance and visual field loss have been equivocal (e.g., Henderson and Burg, 1974), though in a more recent study, it was found that subjects with bilateral visual field defects had rates of accidents and convictions more than twice that of age- and gender-matched controls without bilateral defects (Johnson and Keltner, 1983). Also, simulator studies of peripheral visual field loss have found stronger relationships with accident experience (Szlyk, Severing, and Fishman, 1991). Given older drivers' documented loss of range and flexibility of neck rotation, the age-related decline in visual fields may increase the likelihood of maneuver errors at intersections to the extent that a specific element of geometric design places exaggerated demands on the detection of peripheral objects.

Next, as reported by many older drivers, poorer dark adaptation and heightened glare sensitivity contribute to exaggerated nighttime driving difficulties. Studies have shown a progressive elevation of both rod and cone thresholds with age (Pitts, 1982), with an accelerated loss above the age of 60 that appears to parallel the increase in lens density documented above. The implication of a loss in rod sensitivity is that a much brighter peripheral signal will be needed to elicit proper visual attention from the driver, and that signals now falling below threshold will be ignored. At intersections, the glare—or more specifically, veiling luminance—introduced by roadside light sources and by the traffic signals themselves can be treated as a contrast sensitivity reduction factor, and its effect can be compared with the direct effect of age on contrast sensitivity noted earlier.

Finally, the review of age differences in visual performance addressed the related topics of depth and motion perception. The former examines a person's ability to judge relative distances without reliance on monocular cues (e.g., superposition). 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). However, while accurate perception of the distance to geometric features delineated at intersections, as well as to potentially hazardous objects such as islands, pedestals, and other raised features, is important for the safe use of these facilities, relatively greater attention by researchers has been placed upon motion perception, where dynamic stimuli—usually other vehicles—are the primary targets of interest.

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 they 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,

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[1] Kinematic testing employs a moveable spot of white light that is detected by the subject as it is brought slowly into the field of view from a starting point beyond the field limit. Isopters, or lines of equal detectability (i.e., equal visual field sensitivity), define the field limits for a given spot size and intensity.

building on the previously reported decline of 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 was interpreted as supporting 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. Practical solutions to this (gap judgment) problem were consequently accorded a high priority as an objective in the present project.

Diminished Cognitive Capabilities

Compounding the various 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 attention, decision, and response selection functions crucial to maintaining mobility under current conditions on current system facilities.

Two complementary functions essential to the safe and effective use of intersections are selective attention and divided attention. The first involves the earliest stage of visual attention used to quickly capture and direct attention to the most salient events in a driving scene. The second involves the division of attention between targets of recognized importance to a driver or pedestrian, prior to a vehicle maneuver or intersection crossing decision. The most prominent paradigm that has emerged to address issues of selective attention and traffic safety is the "useful field of view" (UFOV). UFOV measures involve the detection, localization, and identification of targets against complex visual backgrounds (Verriest et al., 1983, 1985). Most importantly, tests assessing the useful field of view are better predictors of problems in driving than are standard 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). A later study by the same researchers that examined the driving records of more than 300 drivers confirmed the predictive power of UFOV. In this study, the correlation between accident frequency and useful field of view exceeded $r = 0.55$; in other words, the UFOV measure alone accounted for more than 30 percent of the variance in accident experience among this study sample (Ball, Owsley, Sloane, Roenker, and Bruni, 1993). This finding is unprecedented in the accident analysis literature. A clear goal of intersection design for older drivers, who experience UFOV deficits to a significantly greater degree than their younger and middle-aged counterparts, must be to reduce the need for lane changes near the intersection, where the demand for attention to potential peripheral conflicts is at its highest.

Next, there is preliminary evidence that older drivers may benefit disproportionately from interventions that compensate for attentional deficits during a high-workload task such as negotiating an intersection. In a field study reported by Hussain, McGee, and Sullivan (1993), a subject's task was to make an appropriate lane selection based on instructions from an experimenter delivered upstream of a complex intersection. The latency of a maneuver decision was consistently longer with ascending driver age, suggesting a possible facilitating effect of providing supplementary highway information to "prime" older drivers who must position themselves properly to accomplish a planned intersection maneuver. In a related effort, a simulator study evaluated the effect of providing advanced left-turn information to drivers who must decide whether or not they have the right-of-way to proceed with a protected turn at an intersection (Staplin and Fisk, 1991). Younger (mean age 37) and older (mean age 71) drivers were tested using animated presentations of intersection traffic control displays, with and without advanced cuing of the "decision rule" (e.g., left turn must yield on green ball) during the intersection approach. Cuing drivers with advanced notice of the decision rule through a redundant upstream posting of sign elements significantly improved both the accuracy and latency of all drivers' decisions for a "go/no go" response upon reaching the intersection, and was of particular benefit to the older test subjects.

This facilitation effect on drivers' maneuver decisions at intersections also attests to the divided-attention problems drivers face in such situations, given the concurrent demands for lane selection and vehicle control for path maintenance, plus vigilance for potential conflicts with other vehicles and pedestrians. A research program carried out at the Traffic Research Centre in The Netherlands has investigated multiple-task performance by older drivers extensively, using time-on-target measures for compensatory tracking in response to "sidewinds" in a simulator presentation of computer-generated driving scenes, plus visual choice reaction-time measures for counting and classifying configurations of filled cells within dot matrices superimposed on the windshield at varying locations. Plotting performance on one task as a function of performance on the other, Ponds, Brouwer, and Van Wolffelaar (1988) constructed performance-operating-characteristic (POC) curves that revealed a clear decline in dual-task performance for elderly subjects, manifested principally through larger performance decrements on the tracking task. Brouwer, Waterink, Van Wolffelaar, and Rothengatter (1991) varied the visual reaction-time (RT) task to compare manual versus vocal reporting and concluded that difficulties in response integration on the visual discrimination task played a significant role in the obtained age differences. Finally, to address the divided-attention demands of active visual search for information at unpredictable locations, Brouwer, Ickenroth, Ponds, and Van Wolffelaar (1990) presented the dot array for the visual-choice RT task peripherally as well as in the driver's central field of view. They influenced subjects' resource allocation strategies through instructions to emphasize one task versus the other (visual discrimination versus tracking) and found that this manipulation affected performance on the visual RT task for peripherally presented, but not for centrally presented, dot patterns. The shifting allocation strategies presumably affected the extent of active visual search (i.e., involving eye movements); this finding suggests that if older drivers must increase their attention to downstream geometric features to make appropriate maneuver decisions during an intersection approach, an impairment in the discrimination of peripheral targets is likely.

Diminished Physical/Psychomotor Capabilities

In this review, physical movement, or psychomotor response, was considered as the output stage of sensory/perceptual and cognitive processing of information from the roadway environment, up to and including decision-making. Given the dynamic nature of the driving task, individuals are *continuously* engaged in the discrimination of "most relevant" stimuli and the subsequent initiation of a best—or at least an adequate—vehicle control response. 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. In this regard, designs that 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 a disproportionately heightened degree of 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). 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.

Other important movement execution factors include movement time and coordination. Movement time—the interval between the initiation of movement and its completion—is significantly slower among the elderly than among the young; age-related motor impairments have been linked to a decrease in muscle mass and elasticity, a decrease in bone mass, and a reduction of central and peripheral nerve fibers (Welford, 1982). In addition, muscular atrophy and related neural losses during aging disproportionately affect the ability to control movement rapidly and accurately (Larsson, Grimby, and Karlson, 1979), and movement corrections during movement execution are slower and much less efficient (Goggin and Stelmach, 1990).

Finally, the age-related slowing of psychomotor responses of older road users reflects a 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 (see Ostrow, Shaffron, and McPherson, 1992). Logically, reduced neck flexibility will also penalize older pedestrians, who must detect potential conflicts without unreasonable delay to accomplish intersection crossings within a protected signal phase. An encouraging finding, however, is that many of the movement execution problems experienced by older road users appear to stem simply from an overall decline in physical fitness among this group, and are amenable to remediation to a significant degree (Ostrow et al., 1992).

INTERSECTION GEOMETRIC DESIGN AND OPERATIONS STANDARDS

Very few studies have examined intersection geometric design and operations standards with respect to driver or pedestrian age. Thus, the material selected for review was included on the following assumption: if it is discovered that road users of all ages are having a problem with a particular design element, then it is reasonable to assume that older road users are experiencing the problem to at least the same degree. Specific design elements for which information was reviewed included:

- Intersection Type
- Vertical and Horizontal Alignment
- Channelization
- Intersection Sight Distance
- Curb Radii
- Traffic Control

Intersection Type

There are three types of at-grade intersections that are commonplace: multiple-leg (five or more), four-leg, and three-leg (T- or Y-type). The multiple-leg intersections are normally the most complex, lead to the most driver confusion, and result in lengthy and complicated traffic control patterns. In general, the safeness of an intersection decreases as the number of legs increase, due to the increase in the number of conflict points.

Zaidel and Hocherman (1987) examined both pedestrian and vehicle accidents over two 3-year periods. The results showed that accident frequencies for both vehicles and pedestrians increased dramatically as the number of legs increased from three to four to five or more. However, the level of exposure was not accounted for in the analysis. Another effort (Hanna, Flynn, and Tyler, 1976) that did control for exposure showed that four-leg and Y-type intersections have much higher accident rates (69 percent and 53 percent higher, respectively) when compared to T-type intersections. The results also show that offset intersections have an accident rate very similar to T-type intersections.

The results of these and other studies reviewed indicate that intersections with three legs, particularly T-type intersections, result in fewer accidents when compared to four-leg and multiple-leg intersections. For this reason, guidelines often suggest the use of T-type intersections. AASHTO provides an example of using two T-type intersections in place of a four-leg intersection to correct an alignment problem, such as a skewed intersection (p. 686, AASHTO, 1990). Another source states that "extensive use of T intersections in residential subdivisions is strongly recommended" (Institute of Transportation Engineers, 1984). In both sources, discussions are included about parameters to be considered when designing such intersections, including "major" and "minor" street traffic volumes and turning movements, minimum offsets between intersections, and traffic control considerations. However, no specific quantitative guidance is provided with respect to any of the parameters.

Intersection Sight Distance

Several studies have shown that sight distance problems usually result in a higher accident rate. A study of intersections in rural municipalities in Virginia showed the accident rate for 41 intersections with restricted sight distances to be 1.33 accidents per million entering vehicles. This was in comparison to 1.13 accidents per million entering vehicles for all 232 intersections included in the study, i.e., an 18 percent increase. The large increase in angle collisions (30 percent) at the restricted sight distance intersections was the primary reason for the higher accident rate. This fact resulted in the authors' conclusion that drivers were unable to adequately view and discern the actions of drivers on the cross streets (Hanna, Flynn, and Tyler, 1976). Unfortunately, since no quantification of the sight distance problem is provided, relationships between the amount of sight distance available and the accident rate cannot be determined.

Collectively, all of the studies reviewed indicate a positive relationship between available intersection sight distance and a reduction in accidents. However, specific information detailing the types of intersections where improvements in sight distance might be advantageous and the amount of accident reduction that could be expected by a quantitative increase in sight distance was not located in this review.

Procedures for determining the appropriate intersection sight distances are provided by AASHTO (1994) for various levels of intersection control and the maneuvers to be performed. The scenarios defined include:

- Case I - No Control.
- Case II - Yield Control.
- Case IIIA - Stop Control—Crossing Maneuver.
- Case IIIB - Stop Control—Left Turn.
- Case IIIC - Stop Control—Right Turn.
- Case IV - Signal Control (should be designed by Case III conditions).
- Case V- Stopped Vehicle Turning Left From a Major Highway (designed by Case III conditions).

For each of the cases listed, a detailed description of the procedures employed and a discussion of the adequacy of the components used in deriving the appropriate intersection sight distances could be prepared. However, this would be a duplication of a current National Cooperative Highway Research Program (NCHRP) study, No. 15-14(1), titled *Intersection Sight Distance* (Harwood, Mason, Pietrucha, Brydia, Hostetter, and Gittings, *in press*). The objective of this study is to evaluate current AASHTO methodology for intersection sight distance for all cases and, where appropriate, recommend new or revised models. Phase I in this research effort included two tasks: (1) a review of the literature as related to driver and vehicle performance and characteristics (including older drivers), intersection characteristics, safety implications, alternative intersection sight distance methodologies, and tort/liability; and (2) a detailed evaluation of the current AASHTO intersection sight distance models and the other models discovered in task 1.

Phase II of the NCHRP study involves the conduct of field studies to assist in choosing between alternative intersection sight distance (ISD) models and quantifying the parameter values of those models.

To avoid duplication of the work in NCHRP 15-14(1), this review focused only on those criteria that may be inadequate for older drivers, primarily perception-reaction time (PRT). Other criteria that are used in design formulas and that are within the domain of the NCHRP study include design speed or prevailing speed of the intersecting highways, acceleration rates and times, pavement width, vehicle length, distance of stopped vehicle from the intersection, driver eye height, and object (opposing vehicle) height.

Considering perception-reaction time (PRT) for at-grade intersections, AASHTO recommends the following values of PRT for intersection sight distance calculations. In Case I, the PRT is assumed to be 2.0 s plus an additional 1.0 s to actuate breaking, although the "preferred design" uses stopping sight distance (SSD) as the intersection sight distance design value that incorporates a PRT of 2.5 s. In Case II, SSD is the design value; thus, the PRT is 2.5 s. For all Case III scenarios and Case IV, the PRT is assumed to be 2.0 s.

A number of research efforts have been conducted to determine appropriate values of PRT for use in intersection sight distance computations. Hostetter, McGee, Crowley, Sequin, and Dauber (1986) examined the PRT of 124 subjects traversing a 3-h test circuit that contained scenarios identified above as Cases II, IIIA, IIIB, and IIIC. Conclusions from the study were that the 2.5-s PRT for Case II was adequate, the 2.0-s criteria for Case IIIA should be retained, and the PRT value for the Case III turning maneuvers (B and C) should be increased from 2.0 to 2.5 s. It is important to note that no significant differences were found with respect to age. A related effort by McGee and Hooper (1983) examined the appropriateness of the PRT values currently specified by AASHTO for computing stopping sight distance, vehicle clearance interval, sight distance on horizontal curves, and intersection sight distance. With respect to the latter, the results showed the following: (1) for Case I, the driver is not provided with sufficient time or distance to take evasive action if an opposing vehicle is encountered; and (2) for Case II, adequate sight distance to permit a stop before arriving at the intersection is not provided, despite the intent of the standard to enable such action. With respect to the PRT values, recommendations include increasing the 2.0- and 2.5-s values used in Case I and Case II calculations, respectively, to 3.4 s. It was also recommended that the PRT value for Case III scenarios be redefined.

More recently, Lerner, Huey, McGee, and Sullivan (1995) conducted four on-road experiments to investigate whether the assumed values for driver perception-reaction time used in AASHTO design equations adequately represent the range of actual PRT for older drivers. Approximately 33 subjects in each of 3 driver age groups were studied: ages 20-40, 65-69, and 70+. The Case III PRT Study included 14 data collection sites on a 90-km (56-mi) route. The Case III (stop-controlled) intersection sight distance experiment found that older drivers did *not* have longer PRT's than younger drivers; in fact, the 85th percentile PRT closely matched the AASHTO design equation value of 2.0 s. The 90th percentile PRT was 2.3 s and there were occasional extremes of 3 to 4 s. The median daytime PRT was approximately 1.3 s. Interestingly, it was found that typical driver actions did not follow the stop/search/decide maneuver sequence implied by the model; in fact, drivers continued to search and appeared ready to terminate or modify their maneuver even after they had begun to move into the intersection. This finding resulted in the study authors' conclusion that the behavior model on which ISD is based is conservative.

In Phase I of their work for NCHRP, Harwood et al. (1993) have suggested that for Case IIIB (left-turn maneuver at stop-controlled intersection), the current AASHTO model may provide sight distances for left-turn maneuvers at stop-controlled intersections that are longer than needed for safety, because (1) drivers perform left turns at these intersections every day with less sight distance than required by the current model and (2) major road drivers often slow down to speeds less than 85 percent of the design speed to accommodate turning maneuvers by minor-road vehicles. AASHTO's assumption in calculating required ISD for CASE IIIB is that the major-road vehicle reduces speed from the design speed to 85 percent of the design speed, and the left-turning vehicle departs from a stop and accelerates to 85 percent of the major-road design speed. Harwood et al. (1993) note that a major concern with the current AASHTO model for Case IIIB is that it is based on an assumption concerning the deceleration behavior of the major-road vehicle that is not backed by field data. The current PRT of 2.0 s for the minor-road driver used in ISD Case IIIB was deemed adequate; however, the PRT requirements of the major-road driver were not determined. The sight distance requirements of Case IIIB (left-turn maneuver) and IIIC (right-turn maneuver) appear to be so nearly identical that the use of the same ISD model is appropriate, according to Harwood et al. (1993). Several alternative models were evaluated in Phase II, including: (1) a modified AASHTO model that accounts for a range of speed reductions by the major-road vehicle and incorporates the PRT of both drivers, (2) a gap acceptance model, and (3) a lag rejection model. The tentative decision to stay with 2.0 s for Case III PRT is based on the Lerner et al. (1995) results that showed that the PRT requirements of older drivers do not differ significantly from those of younger drivers. Finally, a reduction in ISD for Case III intersections may be considered if it can be done without affecting the safety of older drivers.

In summary, there remains a concern about both the appropriateness of the model assumptions and the specific PRT values used in sight distance calculations for meeting the needs of older drivers. Since older drivers tend to take longer in making a decision, especially in complex situations, the need to further evaluate current PRT values still exists. In particular, slowed visual scanning of traffic on the intersecting roadway by older drivers has been cited as a cause of near misses of (crossing) accidents at intersections during on-road evaluations.[2] In particular, health care professionals in the older driver assessment field have noted that in the practice of coming to a stop, followed by a look to the left, then to the right, and then back to the left again, the older driver's slowed scanning behavior allows approaching vehicles to have closed the gap by the time a crossing maneuver is initiated. As a result, the traffic situation has changed when the older driver actually begins the maneuver, and drivers on the main roadway must adjust their speed to avoid a collision.

Alignment

The alignment and profile of an intersection impact upon the sight distance available to the user (both driver and pedestrian) and, thus, affects the ability of the user to perceive the actions taking place both at the intersection and on its approaches. Since proper perception is the first key to performing a safe maneuver at an intersection, it follows that sight distance should be maximized, which, in turn, means that the horizontal alignment should be as straight and the gradients as flat as practical.

Vertical Alignment. The grades at intersections are generally subject to greater restrictions than the open road due to the need for adequate sight distance not only in the forward view, but also to the left and right. The specific criteria provided by AASHTO for vertical alignment at intersections are:

- Substantial grade changes should be avoided.
- Gradients should be as flat as practical, particularly on those sections where vehicles will stop while waiting to perform a maneuver.

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[2] Personal communication, Amy Campbell, Gaylord Hospital Occupational Therapy Department, Wallingford, CT, 3/1/94.

- Grades steeper than 3 percent should be avoided. In the event that such a design is not economically feasible, grades should not exceed 6 percent, and design factors should be adjusted accordingly.

The last criterion is based on vehicle and driver performance characteristics. First, there is little difference in the accelerating and stopping performance of passenger vehicles on grades of 3 percent or less. Second, drivers have more difficulty in judging appropriate stopping or accelerating distances on steeper grades, which may result in increased reaction times. In the event that flat grades are unattainable, adjustment factors are provided in AASHTO's *A Policy on Geometric Design of Highways and Streets* (also known as the *Green Book)* for grades ranging from -4 percent to +4 percent; these factors are to be multiplied by the variable that accounts for the time to accelerate and clear the intersection (AASHTO, 1990).

The evidence to define the impact of grades on safety at intersections is sparse. An effort by Farber (1987) examined the safeness of grades at intersections by simulating a vehicle turning left off the major roadway at an intersection hidden by a vertical curve. The premise for the experiment was that a driver in a following car might not be able to see the turning vehicle in his/her forward path in time to stop on wet pavement due to a reduced sight distance caused by vertical curvature on the approach. The results of the study showed that conflict rates increased rapidly as the sight distance decreased and as traffic volume increased (from 8 conflicts per 10,000 left turns at 150 vehicles per hour to more than 500 conflicts per 10,000 left turns at 900 vehicles per hour). Suggested countermeasures included advance signs warning of left-turning vehicles, which, in turn, will reduce speeds of following vehicles, thus allowing more time for drivers to react.

Horizontal Alignment. Horizontal alignment at intersections takes two forms: (1) alignment of the roadways at the point of intersection, and (2) angle of the intersection. Both impact on the sight distance available and the time required to react and maneuver through the intersection. With respect to the alignment of the roadways, horizontal curvature on the approaches to an intersection is harmful because it is more difficult for drivers to determine appropriate travel paths because their visual focus is directed along lines tangential to these paths (Transportation Research Board, 1987).

Quantitative guidance (e.g., degree of curve) on the amount of horizontal curvature that is permissible is not provided. One study, however, has examined the safety impacts associated with horizontal curvature at intersections. Using 0.5-km (0.3-mi) segments of two-lane highways, four classifications were developed: (1) segments with no intersections; (2) segments with intersections only; (3) segments with intersections and approach curves greater than 4 degrees; and (4) segments with intersections, approach curves greater than 4 degrees, and grades. The results for the four categories produced relative accident rates of 1.0, 2.88, 3.89, and 4.41, respectively. These values indicate a 35 percent increase for segments with "curved" intersections over segments with "straight" intersections (Kihlberg and Tharp, 1968).

With regard to the angle of intersection, all sources agree that right-angle intersections are the preferred design. Decreasing the angle of the intersection makes detection of and judgments about potential conflicting vehicles on crossing roadways much more difficult. In addition, the amount of time required to maneuver through the intersection increases, for both vehicles and pedestrians, due to the increased pavement area. For older drivers, diminished physical capabilities may impact their performance at intersections designed with acute angles by requiring them to turn their heads farther than would be required at a right-angle intersection. This obviously creates more of a problem in determining appropriate gaps. For older pedestrians, the longer exposure time within the intersection becomes a major concern.

The amount of skewness that can be safely designed into an intersection varies depending on the source. The *Green Book* states that provision of an angle of 60 degrees provides most of the benefits that are obtained with a right-angle intersection. Subsequently, factors to adjust intersection sight distances for skewness are suggested for use only when angles are less than 60 degrees (AASHTO, 1990). Another source on subdivision street design states that "skewed intersections should be avoided, and in no case should the angle be less that 75 degrees" (Institute of Transportation Engineers, 1984).

Curb Radii

Curb radii—or the radii of curves that join the curbs of adjacent approaches—impact the following: (1) size of the vehicle that can turn at the intersection, (2) speed at which vehicles can turn, and (3) width of intersection that must be crossed by pedestrians. If the curb radii are too small, lane encroachments resulting in traffic conflicts and increased accident potential can occur. If the radii are too large, pedestrian exposure may be increased (although, if large enough, refuge islands may be provided). The procedures used in the design of curb radii are well detailed in the *Green Book* (AASHTO, 1990). The range of values includes 4.5 m (15 ft) for passenger vehicles in urban areas to 12 m (40 ft) for accommodating large trucks. Studies exploring the safety factor associated with this design element were not discovered.

Channelization

Channelization is defined as "...the separation or regulation of conflicting traffic movements into definite paths of travel by traffic islands or pavement marking to facilitate the safe and orderly movements of both vehicles and pedestrians" (AASHTO, 1990). The most common reasons for using channelization include (ITE, 1984):

- Separation of conflicts.
- Control of angle of conflict.
- Reduction of excessive pavement areas.
- Arrangements to favor predominant turning movements.
- Protection of pedestrians.
- Protection and storage of turning and crossing vehicles.
- Location of traffic control devices.
- Prohibition of specific traffic maneuvers.
- Control of speed.

The *Green Book* provides a number of criteria that should be considered when designing a channelized intersection, including: type of design vehicle, cross sections of the cross roads, projected traffic volumes in relation to capacity, number of pedestrians, speed of vehicles, location of bus stops, and type and location of traffic control devices. Specific quantitative values for these criteria are not provided. However, more detailed guidance can be found in the *Intersection Channelization Design Guide* (Neuman, 1985).

The effectiveness of channelization from a safety perspective has been documented in several studies. An evaluation of Federal Highway Safety Program projects showed channelization to produce an average benefit/cost ratio of 2.31 (Strate, 1980). Another study showed that accidents of all types were reduced by an average of 32.4 percent and injury accidents were reduced by 50 percent where channelization was used (Dale, 1971 and 1973).

One of the most common uses of channelization is for the separation of left-turning vehicles from the through-traffic stream. The reasons for designing intersections with left-turn lanes include: (1) proven safety effectiveness, (2) effectiveness in improving intersection capacity, (3) flexibility in possible signal phasing schemes, and (4) understanding of operation by the driving public. Guidance on when to include left-turn lanes varies with each state as revealed in a survey of practices conducted by Neuman (1985).

The safety benefits of left-turn channelization have been documented in several studies. One study indicates that accidents at signalized intersections with a left-turn lane, in combination with and without a left-turn signal phase, will reduce accidents by 36 percent and 15 percent, respectively. At nonsignalized intersections with painted channelization separating the left-turn lane from the through lane, accident reductions for rural, suburban, and urban areas would be 50, 30, and 15 percent, respectively. If raised channelization devices are used, the accident reductions become 60, 65, and 70 percent in rural, suburban, and urban areas, respectively (McFarland, Griffin, Rollins, Stockton, Phillips, and Dudek, 1979).

Another use created as a result of channelization is the provision of refuge for pedestrians. Refuge islands are a design element that can aid older pedestrians who have slow walking speeds; specifically, the *Manual on Uniform Traffic Control Devices* (MUTCD) states that the function of a refuge island is "to provide a place of safety for pedestrians who cannot safely cross the entire roadway width at one time because of changing traffic signals or oncoming traffic" (FHWA, 1988). While the intent and purpose of the refuge island is well defined, no quantitative warrants are provided by either the MUTCD or AASHTO to determine when such an island is needed. However, areas where they are likely to be needed (e.g., multilane roadways and large or irregularly shaped intersections) are provided in both documents. Once the need is determined, the size and location of such islands can be determined with the help of these two documents as well as *Accessibility for Elderly and Handicapped Pedestrians—A Manual for Cities* (Earnhart and Simon, 1987).

With respect to evaluation studies of the effectiveness of refuge islands, no significant work was discovered. One effort reported that refuge islands specifically installed to address a safety problem were effective in reducing the number of pedestrian accidents (Flora and Keitt, 1982). Citing methodological problems with this analysis (regression to the mean), another source has asserted: "There is a substantial lack of definitive information on this subject, and no conclusions can be drawn" (Smith, Opiela, Impett, Pietrucha, Knoblauch, and Kubat, 1987).

Traffic Control

One of the principal elements of design and operation for an intersection is the type of traffic control device(s). The *Green Book* clearly states that the geometric design should be accomplished simultaneously with the traffic control plan (AASHTO, 1990). Guidelines, including specific warrants, on which level of traffic control is needed are provided in the MUTCD. Since the intent of this project is to focus on the geometric design elements that may impact older road users, a complete review of traffic control research related to intersections has not been conducted. In addition, two other studies are currently underway that are examining older road users and traffic control as part of their objectives. An NCHRP study, titled "Improved Traffic Control Device Design and Placement to Aid the Older Driver" is being conducted at Michigan State University. The literature review in this effort will produce a summary of traffic control devices and practices being used by the states. The second study is the FHWA effort titled "Traffic Operations Control for Older Drivers." This effort is well underway and has produced a list of problems for older drivers at intersections, as well as a number of countermeasures, including potential traffic control solutions.

PROBLEM IDENTIFICATION STUDIES

A series of activities was conducted to better define the problems experienced by older road users at intersections, using various approaches to provide a more comprehensive understanding of the priorities for operational and design improvements to accommodate this group. As described below, these efforts included: (1) a statewide (Michigan) intersection accident database analysis, using a case study approach; (2) a task analysis update 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's Expert Panel of the most appropriate focus of the larger scale laboratory and field investigations to be followed in this project.

ACCIDENT DATABASE ANALYSIS

The accident analysis examined the problems that older drivers and pedestrians have in intersection areas. Approximately 700 accidents were reviewed. As opposed to earlier studies, the analysis was anecdotal rather than statistical in nature. This was because of the abundance of studies that have clearly documented the general problems that older persons have in intersection areas. What has been missing from most analyses of accident databases is an accident-by-accident review of what happened and the determination of the reasons that appeared to lead to the accident occurring. To the extent that the reasons could be pinpointed in the present report, potential solutions—including geometric changes—could then be identified.

The accident data that were reviewed for this analysis primarily came from Troy, Michigan (a fast-growing suburb of Detroit). Troy includes a variety of highway situations, ranging from residential streets to boulevard-type arterials with high volumes. When it was determined that there were few pedestrian accidents identified, the Troy data were supplemented with data from the Lansing/East Lansing area. The latter is the state capital and home of Michigan State University.

The procedure was to identify a set of accidents involving older drivers (either as the at-fault or "other" driver) or pedestrians in the statewide accident database and then retrieve the hard copy of the written accident report form for analysis. In the discussion that follows, comments regarding older drivers are separated from those regarding older pedestrians. A discussion of potential geometric solutions for identified older driver and older pedestrian problems concludes this section.

Accidents Involving Older Drivers

In general, the types of accidents in which older drivers were involved were consistent with what would be expected from the review of the literature; for example, older drivers had problems in yielding the right-of-way and in making left turns. On the other hand, in a large number of accidents, it appeared that the drivers (old and young) were simply not paying attention; thus, for many accidents, there is little that could be done to the highway environment to prevent them. In the paragraphs that follow, several different kinds of accidents are discussed.

The order in which the accidents are discussed below does not necessarily reflect increasing or decreasing accident severity or frequency.

Failure-to-Yield Accidents. The literature suggests that failure-to-yield accidents are especially characteristic of older drivers. This was found to be the case for the accidents reviewed and was, as would be expected, very apparent when older drivers were making left turns. The most prevalent mode of failure was not determined, but typical problems included apparent misjudgment of the speed of the oncoming vehicle and/or the available gap, thinking that the oncoming driver would stop or was going to turn, or simply not seeing the oncoming driver/vehicle.

Good Samaritan Accidents. A typical "good Samaritan" scenario is one where a driver wishes to turn left out of a driveway across three lanes of traffic approaching from the left and merge with traffic approaching from the right. The first two lanes of traffic stop and "wave the driver through" only to have the turning driver hit by a driver in the third lane, which may be less congested with faster moving vehicles. Older persons were often noted as the driver who wanted to make the left turn. There were also several instances where it was an older driver in the third lane that hit the turning driver. While the examples that were encountered tended to be driveway-related accidents (and appeared in the data reviewed because of the proximity of the driveways to intersections), the accidents are also characteristic of those that might occur at unsignalized intersections.

Problems With Recognition/Non-Recognition of Traffic Signals. Another documented problem with older drivers, which would typically result in an angle accident, was an apparent difficulty in noticing or attending to red traffic signals. Anecdotal comments included the older driver not remembering what color the signal had been—presumably either because they did not see it, did not interpret its message correctly, or simply lost the cue amongst the other visual information. While drivers from all ages may be guilty of such infractions, they did seem to come up frequently when the older driver was considered in this review.

Conversely, when older drivers *did* recognize and stop (appropriately) for a signal, they were sometimes rear-end accident victims, i.e., they stopped for a red light only to be rear-ended by the following driver (more often than not, a much younger person).

Finally, older drivers often seemed to "see a signal" and act on it regardless of what else might be happening. For example, in several instances the older driver appeared to start up on the green signal, regardless of whether another conflicting vehicle was in or approaching the intersection. While the older driver did not violate the signal indication *per se*, there was no verification by the driver that it was safe (or clear) to cross the intersection.

Inappropriate Use of Turning Lanes or Turns From Incorrect Lanes. A considerable number of accidents occurred because the older driver failed to use a lane correctly. There were several variations on this problem: a two-way left-turn lane (TWLTL) was not used for turning at all; the TWLTL was entered too far in advance of where the turn was to be made; right turns were inappropriately made from a non-curb through lane; and, left turns were made from the right (curb) lane.

Other turning accidents occurred simply because the older driver ignored turning-movement restrictions (e.g., turned left when left turns were prohibited).

Median U-Turn Accidents. On boulevards, a fairly common technique used in Michigan to avoid left turns at high-volume intersections is to have would-be left-turning vehicles go through an intersection and use a median crossover to reverse directions and then make a right turn (e.g., an eastbound driver that wishes to turn north at an intersection continues eastbound through the intersection, uses a crossover to reverse direction to the west, and then turns right [north]).

In the several crossover accidents that were reviewed, the older driver was invariably at least partially at fault. They generally misjudged the maneuver and their vehicle's position with respect to proximity to other vehicles in the crossover itself, or crashed with other vehicles upon leaving the crossover area. While the crossover maneuver is not an easy one to accomplish, nor necessarily widely used elsewhere, the accidents at such locations provide insight into the problems that older drivers have with this and other types of channelization.

Vehicle Alignment and Guidance Problems—Left Turns. Another class of problems for older drivers in intersections relates to the misjudging of distances in general, and specifically, where the vehicle is with respect to placement in the travel lanes, and where the vehicle is in relation to other vehicles.

First, there are problems with respect to older drivers positioning their vehicles within the intersection. For example, a number of turning accidents occurred with the following scenario: the older driver was turning left at an intersection with a permitted signal; opposing traffic was using three or more lanes (e.g., one left-turn-only lane, a through-only lane, and a through and right lane); and the older driver would strike a vehicle in the oncoming curb (right or through and right) lane. That is, the older driver would have an accident during the very last part of the decision sequence. The problem would seem to be one of misjudging how long it will take to make the turn (traversing several lanes) or the distance that needs to be covered before the oncoming vehicles will conflict with the turning vehicle.

Another accident outcome with the same turning scenario has the older driver turning left and "clipping" the vehicle in the lanes to the driver's immediate left (e.g., a driver making a northbound-to-westbound left turn would "clip" eastbound drivers waiting for the signal to change). This was noted as a problem that was not exclusively one of older drivers. There are several potential causes of this sort of accident: the turning driver was "hurried" by oncoming drivers and turned short to avoid them; the waiting vehicle was beyond the stop line; or the driver simply misjudged the positions of his/her own vehicle and other vehicles.

Finally, older drivers also seem to be prone to making misjudgments in using right- and left-turn lanes (or flares). There were several instances when older drivers who were attempting to move into the turning lanes collided with vehicles that were already in the lane (e.g., in the older driver's "blind spot"). This same sort of problem is likely with the older driver moving from the flare or terminating lane to the adjacent through lane.

Vehicle Alignment and Guidance Problems—Right Turns. Another class of turning accidents in which older drivers seem to be over-involved is the right-turning vehicle "swinging wide" into the curb lane and encroaching on the next lane over. This is a combination of controlling the vehicle's path and misjudging the proximity of vehicles in adjacent lanes. This accident type could occur at any intersection or driveway.

Accidents Involving Older Pedestrians

Accidents involving pedestrians were also investigated, although many fewer incidents could be identified. There were even fewer instances where there were marked differences between the accidents involving older and younger pedestrians. The accidents that were reviewed for this part of the analysis included those from Troy and some from East Lansing.

Many pedestrian accidents occurred, as might be expected, when the pedestrian was adjacent to the roadway (typically not on a sidewalk). Several pedestrians were simply walking (in the same direction as traffic), some were hitchhiking, and some were with their vehicles that had broken down. Several were noted as having been drinking.

Other pedestrian accidents occurred when the pedestrian came from between cars (several younger people in this category) or just "stepped off the curb." There were at least a couple of instances when the pedestrian appeared to have been maliciously hit by drivers. Most pedestrians that were hit were not in crosswalks. This was especially the case with the East Lansing pedestrian accidents where most of the accidents seemed to involve younger people whose own actions were the cause of the accident (e.g., darted into traffic).

Two types of accidents that are related to geometry and intersection design are those involving right-turn-on-red (RTOR) movements and pedestrians coming from in front of a stopped bus. RTOR accidents generally occurred when either the turning driver, the pedestrian, or neither was paying attention to the other.

Solutions Involving Geometric Changes

The range of older driver accident experiences described above was associated, through engineering judgment,[1] with potential solutions involving geometric changes.

To begin with the "good Samaritan" accident type, older drivers' problems in these situations could be described as a "failure" at or near the end of the decision sequence. Similarly, the (older) driver who hits the turning vehicle is typically taken by surprise by an unexpected maneuver. The situation provides some insight into how drivers, and especially older drivers, respond to complex and unexpected situations—poorly. An initial conclusion in this review is that to the extent that geometric changes can help reduce the complexity or the probability of an unexpected event, they will more likely have (disproportionately) beneficial effects for older road users.

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[1] Personal communication, Prof. Richard Lyles, Department of Civil and Environmental Engineering, Michigan State University (project consultant), 8/20/93.

Regarding "failure-to-yield" crashes, the most logical way to correct the left-turn-related accident of this sort would be to restrict left turns at certain locations (e.g., for unsignalized intersections) or change from permitted to protected phases for signalized intersections. The guideline of complexity reduction must again be emphasized. If changes must be made for operational reasons (e.g., to increase level of service), they should be done in the simplest way possible.

The most common element in potential geometric solutions is channelization. For example, a possible countermeasure for inappropriate-use-of-turning-lanes accidents at intersections with heavy right-turning movements could be a small, but conspicuously marked, island physically separating the turning lane (and vehicles) from the through lane (and vehicles). This would serve both to reinforce the need for the driver to make a decision regarding a potential turn during the intersection approach, and to limit the ability to make "last second" turning maneuvers from an incorrect lane. In the latter instance, a vehicle in the rightmost through lane would be prohibited from changing to the right lane by the channelization.

At the same time, channelization in such situations may also be perceived by the driver as simply adding more confusion to an already complex situation. Clearly, adding an island with its incumbent markings and (probably) increased intersection size represents a net increase in the cues that must be processed by the driver negotiating the intersection, which may already have numerous lane restrictions, several traffic control devices (including potentially complex signalization), and, most likely, high traffic volumes.

Also, for some drivers who make a "late merge" into the turning lane or who simply make the turn from the incorrect lane, channelization may simply change the place or nature of the accident. For example, for right turns, the decision point for merging into the turning lane for a channelized intersection may just be moved upstream—the problem is not solved, just moved. Likewise, drivers who make the turn from the incorrect lane (in spite of the traffic in the adjacent lane) may not be deterred at all by the island, either hitting it or simply thinking that they are in the curb (appropriate) lane.

Another potential problem with right-turn channelization is the position of the vehicle when the driver has to merge with traffic approaching from the left. With a right-turn channel where the driver must look to their left before completing the turn (e.g., RTOR situations), drivers are more likely to be forced into a "looking over their shoulder" mode (versus simply looking to their left)—this will present an additional problem for any driver with restricted physical capabilities (e.g., someone with arthritis), a more common occurrence among older persons.

With respect to the TWLTL-related problems, channelization would not seem to be an option. However, wider TWLTL's may allow drivers a greater safety margin in avoiding vehicles entering, leaving, and generally misusing the lane (e.g., using it to bypass stopped vehicles in advance of a left turn at an intersection).

The three accident types involving alignment problems during left turns all occur in intersections that are complex. They have multiple lanes, mixed use of lanes, relatively large distances that need to be traversed to complete maneuvers, complex signalization, and numerous conflicting maneuvers by other vehicles. The improvements to such situations would include any steps that could be undertaken to simplify the activities required or to clarify what those activities are.

For vehicle alignment problems in right turns, a potential geometric treatment could be to increase the radius of the curb or, if not in a curbed section, the inside edge of the pavement. This would allow the turning driver to start the turning maneuver earlier, which should serve to decrease the likelihood of straying into the adjacent lane. Likewise, it should also provide an extra margin of safety for the turning drivers when merging with drivers/vehicles already in the lane.

In consideration of potential geometric solutions to accidents involving pedestrians "along the road," improvements that could be made include more sidewalks, better/wider shoulders, and paved shoulders. All of these provide the pedestrian better refuge. However, it is not clear whether any of the accidents that were reviewed would have been prevented by these modifications—the accident reports typically did not provide accurate, if any, information regarding how far off the edge of the pavement the pedestrians had been (if at all) when they were hit. For the bus-related accidents, the only geometric change that might improve the situation would be to have bus pull-off spaces so that the pedestrian can look around the bus at oncoming traffic from the sidewalk rather than from the street at the front of the bus.

Finally, the potential may be noted to exaggerate older pedestrians' problems in turning situations (e.g., when struck by an RTOR vehicle) as the result of separate turning lanes, wider lanes, and acceleration flares. All of these treatments tend to encourage "quicker" turns on the part of the driver, while increasing the distances that pedestrians have to negotiate.

INTERSECTION APPROACH TASK ANALYSIS UPDATE

A limited task analysis update was performed to help identify potential problems of older road users by pinpointing mismatches between specific task requirements during intersection approach driving with documented age-related deficits in performance capabilities needed to accomplish these tasks. This task analysis update used task descriptions generated by McKnight and Adams (1970) as its starting point. The tasks required of drivers in this context encompass surveillance, steering, speed control, "urban driving," car following, lane changing, and negotiating intersections as inventoried in the prior analysis. An intersection approach was thus described using 10 *main tasks*:

(1) Maintain speed of traffic flow.
(2) Maintain correct lateral lane position.
(3) Surveillance (of traffic and pedestrian conditions, traffic signs, pavement markings, physical barriers, and traffic signals).
(4) Attend to in-vehicle controls and displays.
(5) Determine proper lane position for intended downstream maneuver.
(6) Enter correct lane.
(7) Decelerate for stop-controlled intersection.
(8) Reinforce (if advanced information was available and processed) or obtain information about intersection movement regulations.

(9) Adjust speed in anticipation of signal phase expected upon reaching intersection.
(10) Search for path guidance cues for aiming vehicle across intersection or through turning maneuver.

These main tasks were then re-described in terms of the operations (units of behavior) required of the driver to perform them. The resulting hierarchical task analysis (HTA) is shown in Figure 1. Where performance of a particular task or its operations is explicitly determined by the geometric configuration of an intersection, it is identified in the HTA by a bold box outline.

Next, this subset of tasks was subjected to a decomposition analysis, breaking the tasks down into categories chosen to describe the functional capabilities required for safe and effective performance. This level of task decomposition provided the specificity of requirements for drivers' responses in this operational context needed to pinpoint potential errors resulting from mismatches between a specific geometric element and older drivers' cognitive, perceptual, and/or physical capabilities.

It may be noted that older drivers display deficits in the performance of many of the tasks identified in Figure 1 that are **not** directly related to geometry, such as determining relative speed and distance of other vehicles, and the detection and processing of traffic control device information. However, these tasks were outside the scope of the present decomposition analysis. Accordingly, a task decomposition was performed for the following five tasks listed in the HTA: 2.0 (Maintain correct lateral lane position); 3.3 (Survey pavement markings); 3.4 (Survey physical barriers); 5.0 (Determine proper lane position for intended downstream maneuver); and 10.0 (Search for path guidance cues).

Six categories were chosen to describe the functional requirements and consequences of mismatches for the performance of each of the five tasks listed in the decomposition analysis. Listed for each task are: (1) the look location, (2) visual/perceptual requirements, (3) cognitive requirements, (4) control movements, (5) potential errors, and (6) the relevant geometry and/or operation determining performance of the task. Tables presenting the results of the decomposition analysis are included in Appendix A, with principal findings discussed below.

The visual/perceptual requirement common to the performance of all five tasks is contrast sensitivity (for detecting lane lines, painted roadway symbols and characters, curbs and roadway edge features, and median barriers). The discrimination at a distance of gross highway features—rather than fine detail as contained in a sign message—is what governs drivers' perceptions of intersection geometric elements. Thus, conspicuity of these elements is of paramount importance in the task of safely approaching an intersection and in choosing the correct lane for negotiating the intersection. The smaller the attentional demand required of a driver to maintain the correct lane position for an intended maneuver, the greater the attentional resources available for activities such as the recognition and processing of traffic control device messages, detection of conflict vehicles and pedestrians in the periphery, and execution of hazard-avoidance maneuvers.

Specifically, this task analysis indicated that the early detection of downstream channelization, achieved by cuing the driver in advance that designated lanes exist for turning and through maneuvers, will promote safer and more confident performance of any required lane

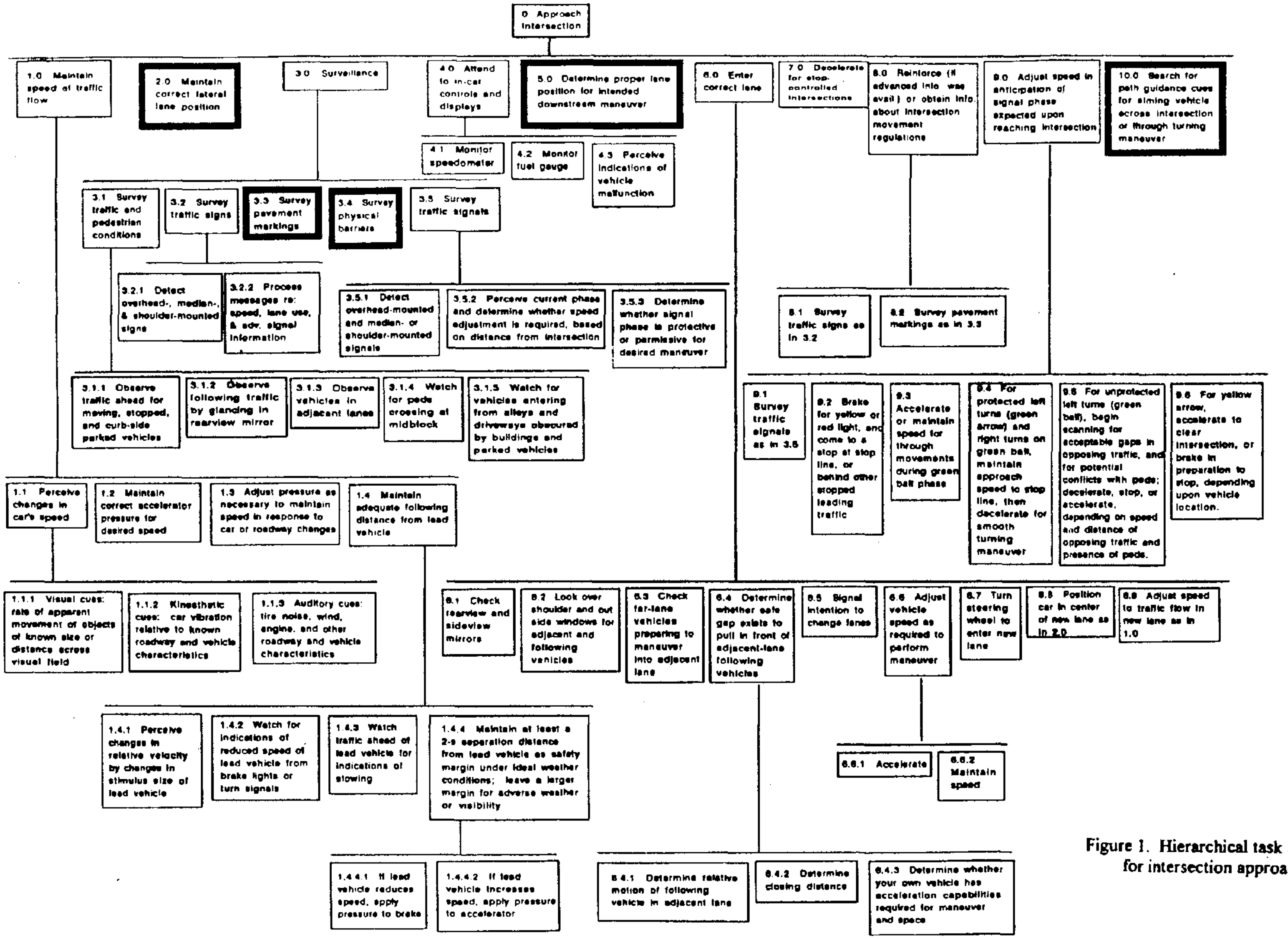

Figure 1. Hierarchical task analysis for intersection approach.

changes. This is because the traffic density is lighter, there are more available gaps, and there are fewer potential conflicts with other vehicles and pedestrians the farther away from the intersection the maneuver is performed. Of course, even the brightest delineation and pavement markings will not be visible to an operator unless an adequate sight distance (determined by horizontal and vertical alignment) is available. Overhead signing is particularly useful in this regard to ensure appropriate responses to intersection geometric elements.

Curb and median conspicuity, besides aiding in the visual determination of how an intersection is laid out, is especially important when medians are used as pedestrian refuges. In this instance, care must be taken to ensure that pedestrian refuges are clearly delineated and made as visible as possible to passing motorists.

In the same vein, the task analysis highlights a need for regulatory, warning, and guide signs posted in advance of, as well as at an intersection, to provide information to drivers about movement regulations that may be difficult to obtain from painted arrows when traffic density is high or when pavement markings are obscured by snow or become faded, or where sight distance is limited. Older drivers (as well as their younger counterparts) have been shown to benefit from redundant signing upstream of intersections (Staplin and Fisk, 1991). In particular, drivers should be forewarned about lane drops, shifts, and merges through advance warning signs. Advance route or street signing, as well as confirmatory signing/route assurance assemblies across the intersection, will aid drivers of all ages in deciding which lane will lead them to their destination, prior to reaching the intersection.

The importance of presenting drivers with appropriate information about where to go and which lane to be in during an intersection approach, as indicated in this analysis, underscores a fundamental interrelationship between geometric and traffic control elements in intersection design. Uncertainty, be it about guidance, navigation, or traffic regulation, produces hesitancy in executing maneuvers, which decreases available maneuver time and diminishes the attentional resources available for effective response to the dynamic nature of potential traffic conflicts, which reaches a peak at and near intersections. Older drivers will be disproportionately penalized by such demands.

In summary, older drivers' decreased contrast sensitivity, reduced useful field of view, increased decision time—particularly in response to unexpected events—and slower vehicle control movement execution combine to put these highway users at greater accident risk when approaching and negotiating intersections. In considering the relative importance of mismatches between older driver capabilities and requirements for safe and effective response to intersection design elements, a set of potential problems were identified and preliminarily ranked in this task analysis in terms of the seriousness of resulting driver errors:

(1) Inadequate upstream, advance warning/advisory information to support driver decision making about proper lane selection for safe negotiation of the intersection.

(2) Channelization for designated traffic movements at an intersection that is ineffective due to lack of conspicuity and/or comprehensibility by drivers during the intersection approach, producing uncertainty about the correct lane position for an intended maneuver at the intersection.

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(3) Physical barriers in median and shoulder areas with inconspicuous raised surfaces, either vertical or sloping, which can lead to a loss of vehicle control if struck by an unaware driver.

Finally, while the emphasis of this analysis has been on the more demanding, dynamic information-processing tasks confronting an (older) driver during an intersection *approach*, at least two other scenarios where geometric elements may produce or exacerbate problems for this group may be identified.

First, a well-marked, highly conspicuous left-turn storage bay might be described as a "good" design to the extent that it is effective in safely channelizing turning drivers during an intersection approach. Safety problems may result, however, depending upon its alignment with respect to the same feature on the opposite leg; if opposite left-turn lanes are negatively offset, a severe sight distance restriction typically results when an opposing turn queue develops.

Also, after a stop, when scanning to determine clearance for a turning or crossing maneuver, a driver's response effectiveness can be influenced by any significant restriction in the range and flexibility of head/neck movement. At a skewed intersection, for example, an older driver's scanning of traffic on the acute angle approach of the intersecting roadway will certainly be slowed, and may be less efficient in terms of target detection. There is a similar concern associated with the angularity at the gore of a channelized right-turn lane with through traffic on an intersecting roadway; errors in merging decisions and in the timely performance of merging maneuvers by older drivers are likely to increase as the angularity of this geometric element departs from 90°.

OLDER ROAD-USER FOCUS GROUP DISCUSSIONS

Another approach to identifying the problems experienced by older road users at intersections undertaken in this project was to conduct focus group discussions with 6-8 individuals at a time, recruited as described below. This activity included the completion of an intake questionnaire addressing intersection use patterns as well as more general information regarding driving history and exposure. The discussion groups lasted 2 to 2-1/2 hours per session. When summarizing and interpreting the findings from this project activity, tape recordings of focus group sessions in a related FHWA project, "Traffic Operations Control for Older Drivers" (Contract No. DTFH61-91-C-00033), were also reviewed to extract comments specific to intersection geometric elements that were not of primary concern in the other effort.

Sample Recruitment

A total of 81 older road users, subsequently assembled in 11 discussion groups, were recruited as paid study participants at locations designed to ensure the best possible cross section of this highly diverse segment of the population. It may be noted that the group discussions were conducted in a suburb of Philadelphia, PA. Eight- and sixteen-kilometer rings around this meeting site encompass urban, suburban, exurban, and rural driving environments. Travel times of up to 45 minutes were required of persons agreeing to participate in this project activity. Thus, a sampling of older study participants who are commonly exposed to a wide range of intersection types was permitted.

The primary recruitment effort for this study took place at three Pennsylvania photo license centers, where an individual's date of birth (day of year) determines who walks through the door at any given period of time. Additional recruiting was accomplished through visits to local Senior Adult Activity Centers and by placing ads in the Senior Center newsletters; this additional sampling accounted for 37 percent of the sample. The requirements for participation were that each individual is: (1) an active, licensed driver; (2) exposed on a regular basis to a meaningful range of different urban and suburban intersection situations as a driver and/or pedestrian; and (3) not related to or acquainted with any other member of his/her discussion group.

The composition of each group included a mix by age and gender of individuals from among the total sample recruited for this project activity. Overall, two older driver age categories were recruited equally: (1) "young-old" individuals, ages 65-74, and (2) "old-old" persons, age 75 and older. The resulting sample was composed of 57 percent young-old and 43 percent old-old participants, distributed by age and gender as reported in Table 1.

Table 1. Characteristics of focus group participants.

Age Group	Number of Participants	Number of Females	Number of Males	Age Range	Mean Age	Median Age
65-74	46	22	24	65-74	69	68
75+	35	12	23	75-86	79.8	79

Group Discussion Protocol

As participants arrived at the meeting place, they were greeted and asked to complete a driving profile questionnaire to characterize the driving practices of the sample. Specifically, they were asked to indicate their annual mileage; the number of trips they make each week; the proportion of time they spend driving on freeways, arterials, and residential roadway types; and the percentage of time they drive in familiar versus unfamiliar locations. This information is summarized in Table 2 by age group and by gender within age group. This table indicates that the females in both age groups drive approximately the same number of miles per year, but the old-old males drive about 32 percent less than their young-old counterparts. The young-old males also spend slightly more time driving on high-speed roads than the old-old males. Not surprisingly, both groups drive much more often in familiar locations than in unfamiliar ones.

Table 2. Focus group participant driving profile.

Group	Mean Annual Mileage	Mean Trips per Week	Mean Percentage of Overall Driving On:				
			High-Speed Roads (55 mi/h)	Moderate-Speed Roads (35-55 mi/h)	Low-Speed Roads (25-35 mi/h)	Familiar Locations	Unfamiliar Locations
65-74 Males	14,092	11.6	44.5	36.8	19.6	73.3	28.0
65-74 Females	5,000	9	33.4	34.9	35.4	74.7	26.4
65-74 All	9,348	10	38.8	35.8	27.8	74.0	27.0
75+ Males	9,598	9.2	38.6	37.1	24.3	80.0	20.0
75+ Females	5,188	6.1	30.1	36.8	35.6	81.1	22.7
75+ All	8,086	8.0	35.9	37.0	28.2	80.4	20.8

1 mi = 1.61 km
1 mi/h = 1.61 km/h

As each group convened, approximately 20 minutes were allotted to complete an intake questionnaire to assess the frequencies with which different types of intersections were experienced by each group member. A set of 25 diagrams was prepared, showing 1 intersection in plan view per page. Frequency-of-use checklists with five response categories accompanied each diagram, one to describe the individual's level of experience as a driver and the other to describe his/her experience as a pedestrian. The (frequency-of-use) response options were: *never*, *rarely* (once a month or less), *occasionally* (2-3 times per month), *often* (once or twice a week), and *very often* (more than twice a week). One clear finding is that this group of participants encountered intersections much more frequently as drivers than as pedestrians. The intersection diagrams prepared for this questionnaire highlighted geometric elements, including:

- Single-lane (same direction), two-lane, and three-lane approaches.
- Turning operations with and without storage lanes.
- Single and dual left-turn lanes.
- Positive, negative, and aligned opposite left-turn lanes.
- "Jughandle" geometries for left-turning movements.
- Median U-turn lanes (indirect crossover) followed by right turns for left-turning movements.
- Intersection approaches that include opposing traffic streams separated by a median, by delineation between adjacent lanes only, and by two-way left-turn lanes.

- "Right lane must turn" operations, with and without a pavement width transition upstream of the intersection.
- Auxiliary turning lanes for right turns, with immediate and delayed merge into the traffic stream on the intersecting roadway.
- Three-leg (T-type) intersections.
- Oblique angle intersections.
- Intersections where the alignment of two legs on the same roadway is offset.
- Pedestrian refuge islands with and without physical barriers.
- Variably rounded curb cuts at corners.

In addition, as each participant completed this questionnaire by checking off the appropriate frequency-of-use category for each intersection depicted in the various diagrams, he/she highlighted any feature that "would pose special problems or which would be avoided if possible." At the completion of the questionnaire by all participants, a 5-minute break was offered to allow for the identification of the geometric elements most often highlighted as problematic by the group participants. The group leader then began the discussion by referring to the tally of most frequently highlighted problem elements, as determined by the group observer's review of questionnaire responses during the break. The objective was to determine the degree of consensus regarding each element in question as a problem, and to pin down the reason(s) older road users experience difficulty with that element.

The next objective was to identify specific sites that each participant could visualize to help explain why the feature in question was problematic, and also to generate a list of candidate intersection stimuli for the preliminary laboratory study to be conducted as a later activity in this project. Each group member was given an opportunity to identify a site from his/her own experience, and a diagram that attempted to condense or generalize the critical element(s) common to each member's experience was produced on a flip chart by the group leader.

Finally, the group leader elicited comments regarding the exact nature of the problem by probing for responses relating to vehicle steering control, vehicle speed control, conflict avoidance, navigational decisions, right-of-way decisions, pedestrian crossing decisions, etc.

Focus Group Results

Pertinent findings from the discussion generated within this framework were summarized to: (1) determine the degree of consensus regarding a given problem, (2) identify specific sites/examples of problem geometric elements, and (3) describe the nature of specific actions or decisions required of the driver that cause difficulty. These results are presented in text and tables below, segregated by age cohort. In addition, it should be noted that the responses reported in Table 3 are rank-ordered in terms of (decreasing) subjective importance to the older group participants; this was done according to the frequency of mention and the degree of agreement with which a comment was received by a group, based on both verbal and nonverbal (e.g., head nodding) behaviors.

Table 3. Geometric features identified as sources of difficulty by older drivers participating in focus group sessions.

Geometric Feature	% for Which Feature Is a Problem	% for Which Feature Is Not a Problem	% Offering No Opinion	Nature of Problem(s)	Related Operational and Traffic Control Issues
Skewed junction on one or more legs of intersection	Y-O: 71% O-O: 77% All: 74%	Y-O: 7% O-O: 0% All: 4%	Y-O: 22% O-O: 23% All: 22%	Difficulty turning head to the left to watch traffic approaching on the main line, due to reduced flexibility of muscles and pain from arthritis	Speed of traffic on main line Presence of traffic signal
Tight intersection corner radius	Y-O: 74% O-O: 74% All: 74%	Y-O: 0% O-O: 3% All: 1%	Y-O: 26% O-O: 23% All: 25%	Visibility problem with sharp corners Problem hitting curbs and median barriers With sharp turns, trucks turning left into adjacent opposing traffic lane end up face-to-face with drivers, requiring them to back up	Staggered (offset) stop bars to facilitate left turns Protected turning signal phases where sight distance is restricted
Median elevation for left-turn storage bay channelization	Y-O: 65% O-O: 77% All: 70%	Y-O: 17% O-O: 14% All: 16%	Y-O: 18% O-O: 9% All: 14%	Difficulty seeing barriers, particularly at night and in the rain, and therefore they become obstructions that drivers are concerned about hitting The left-turn lanes are not long enough to store all the drivers who want to turn left. This results in through traffic blocking the entrance to the left-turn bay, as well as backing up left-turn traffic into the through lane, and blocking through traffic. Drivers preferred to have painted medians to allow them to get into the left lane.	Flat (painted) medians

Table 3. Geometric features identified as sources of difficulty by older drivers participating in focus group sessions (continued).

Geometric Feature	% for Which Feature Is a Problem	% for Which Feature Is Not a Problem	% Offering No Opinion	Nature of Problem(s)	Related Operational and Traffic Control Issues
Turn-only lanes	Y-O: 63% O-O: 66% All: 64%		Y-O: 37% O-O: 34% All: 36%	Drivers all of the sudden find themselves in the wrong lane, either because they have certain expectations about lane use derived from intersections encountered on the same roadway (i.e., the right lane is both right turn and through in one location, but in another, it becomes right turn only, and the left lane is through and left turn), or the advance signing is inadequate or lacking, and pavement markings are covered by cars at the intersection.	Advance warning, via redundant lane-use signs placed overhead, coupled with roadside signing and traverse pavement "ONLY" markings
Acceleration lane in right-turn operations	Y-O: 63% O-O: 43% All: 54%	Y-O: 26% O-O: 40% All: 32%	Y-O: 11% O-O: 17% All: 14%	Problems caused by impatient following drivers cutting around older drivers in an acceleration lane (potential collision) Problems caused by drivers "freezing" in an acceleration lane (potential rear-end collision) Difficulty merging with fast traffic on the main line Difficulty seeing traffic approach on main line from the left, due to angle (skew)	Choice of regulatory sign (STOP or YIELD)
Pavement-width transition (lane drops) across intersection	Y-O: 50% O-O: 49% All: 49%	Y-O: 4% O-O: 6% All: 5%	Y-O: 46% O-O: 45% All: 46%	Need more room on the other side of the intersection because "it's always a squeeze/race to see who can get there first"	Multiple warning signs

Table 3. Geometric features identified as sources of difficulty by older drivers participating in focus group sessions (continued).

Geometric Feature	% for Which Feature Is a Problem	% for Which Feature Is Not a Problem	% Offering No Opinion	Nature of Problem(s)	Related Operational and Traffic Control Issues
Dual left-turn lanes	Y-O: 24% O-O: 49% All: 35%	Y-O: 24% O-O: 26% All: 25%	Y-O: 52% O-O: 25% All: 40%	Concern that driver in adjacent lane will encroach into driver's lane Problem merging on the other side of the turn if both lanes merge shortly after the turn Problem if an immediate lane change is required on the other side of the turn to enter a driveway/parking lot Problem hitting median barrier (from inside/left lane) or curb (from outside/right lane) in attempt to remain within lane boundaries through the turn	Delineation through the turn Advance dual left-turn lane advisory signs Advance information about each lane's destination (i.e., proper lane for mall/ shopping center entrances on other side of the turn)
Center two-way left-turn lanes	Y-O: 24% O-O: 20% All: 22%	Y-O: 13% O-O: 23% All: 17%	Y-O: 63% O-O: 57% All: 61%	Risky and uncomfortable because of the potential to get stranded when confronted with an opposite left-turning driver It's generally confusing Snow covers the arrows on the road	Pavement markings (arrows) to indicate sections of highway where only one direction of travel can turn from the center turn lane
Elevation of channelization for right-turn operations	Y-O: 26% O-O: 17% All: 22%	Y-O: 48% O-O: 54% All: 51%	Y-O: 26% O-O: 29% All: 27%	Difficulty seeing barrier (due to older drivers' reduced contrast sensitivity), reducing it to an obstacle/hazard with which a driver may collide	Flat (painted) medians

Table 3. Geometric features identified as sources of difficulty by older drivers participating in focus group sessions (continued).

Geometric Feature	% for Which Feature Is a Problem	% for Which Feature Is Not a Problem	% Offering No Opinion	Nature of Problem(s)	Related Operational and Traffic Control Issues
Channelized vs. non-channelized right-turn operations	Y-O: 22% O-O: 20% All: 21%	Y-O: 54% O-O: 49% All: 52%	Y-O: 24% O-O: 31% All: 27%	Difficulty turning head to see traffic coming from the left (skewed intersection problem) More likely to have conflicts with pedestrians than if the lane came up to the intersection, because pedestrians stray into the street when they have one lane to cross Potential for accidents when drivers entering the main line from the channelized lane cut in front of main line drivers without yielding	Signing at end of channelized lane (STOP vs. YIELD)
Angle of offset for opposite left-turn lanes	Y-O: 2% O-O: 0% All: 1%	Y-O: 13% O-O: 6% All: 10% (given a protected left-turn phase)	Y-O: 85% O-O: 94% All: 89%	Tradeoff between being able to see past row of opposite left-turning drivers when left-turn lanes are aligned, and higher comfort level resulting from not being face-to-face with other turning drivers when opposite turn lanes are not aligned	Presence or absence of protected left-turn phase Delineation through the turn

While the data reported in Table 3 are largely self-explanatory, there were several other design issues discussed by the focus group participants that deserve mention. One feature about which almost everyone responded positively was the jughandle design. Overall, 76 percent of the group agreed that entirely eliminating left turns across busy roadways through the use of jughandles was a safe and convenient practice. However, 22 percent of this group qualified this statement with the fact that it was only a good idea if lots of advance warning was given.

Another feature not diagrammed but discussed, was the traffic circle, or roundabout. Twenty-eight percent of the participants voiced a negative opinion about traffic circles, stating, "you never know who has the right-of-way," and "they are really a problem when you don't know where you're going."

A key topic addressed in each discussion session was the question of whether the design of intersections should prioritize the ease of use and/or safety of one population of road users over another—drivers versus pedestrians. Collapsed across driver age, 66 percent of the participants said intersections should be designed for the driver and 34 percent said intersections should be designed for the pedestrian. Thirty-four percent of the group choosing the driver stated that there are more drivers than pedestrians, so engineers should design for the majority. Within the young-old group, 78 percent of the participants said intersection design should favor the driver, while the remaining 22 percent said the pedestrian should be considered more than the driver. The old-old group was roughly evenly split in their opinion as to who the design should favor, with 52 percent choosing the driver and 48 percent choosing the pedestrian. About twice as many old-old drivers as young-old drivers thought more consideration should be given to pedestrians at the expense of drivers. One of the old-old drivers favoring designing for the pedestrian said, "It's a good idea for pedestrians to have barriers to stand on, but barriers can be dangerous for drivers. However, if the barrier were high enough and properly marked, drivers would see it and would be cautious about not hitting it." Overall, equal percentages of male and female study participants (66 percent of the males and 67 percent of the females) stated that intersections should be designed for the ease and safety of drivers, at the expense of pedestrians, if it came down to that tradeoff. Another perspective, expressed by a minority of participants, asserted that, "You have to design for what's going on at the intersection. If you are in an area where there are a lot of pedestrians, then you should design for pedestrians."

Findings From Related Group Discussions

As noted earlier, focus group discussions on the related topics of traffic and pedestrian control devices were performed as part of FHWA project DTFH61-91-C-00033 (see Reinfurt, Council, Zegeer, and Popkin, 1992). A total of 85 active, older drivers participated— 60 persons ages 65-74, 22 persons age 75+, and 3 of unknown age. The sample was divided roughly equally between males and females. Although these individuals were distributed across four geographical locations—Washington, DC; Chapel Hill, NC; Tampa, FL; and Phoenix, AZ—the extraction of comments pertaining to specific aspects of intersection geometry and operations as summarized in the bulleted list below reflects a composite of all of the group discussions. Problems with intersection geometric elements identified in the Reinfurt et al. effort included:

- *Turn-Only Lanes*—Drivers reach the intersection and find that they are in the wrong lane, due to insufficient warning of turn-only lanes ahead. There was strong agreement that **overhead** advance warning signs are the required "fix."

- *Pavement-Width Transitions*—Drivers reported difficulty negotiating lane-drop situations encountered across intersections, because the merge distances are too short and there is not enough advance warning. Difficulties by right-turning drivers who must merge when an acceleration lane ends are included in this category.

- *Dual Left-Turn Lanes*—Frequently, problems occur when: (1) the lanes are not delineated through the turn, and (2) the two lanes merge into one lane soon after the turn. Discussion indicated the need for advance information advising which lane to take to turn into a particular destination on the other side of the intersection, and for a turning radius that is wide enough to allow for easy maneuvering.

- *Intersection Width (and Pedestrian Crossing Time)*—Older pedestrians have problems crossing streets either because the street is too wide and the pedestrian signal does not allow enough time for them to complete their crossing, or because they just walk too slowly. Most agreed that a pedestrian refuge is an acceptable solution, and several suggested extending the length of the protected pedestrian phase to take more diminished-capability individuals into account.

- *Pedestrian Refuge Islands*—Vulnerability as pedestrians was cited in identifying a problem of the median refuge island being too narrow, with traffic on both sides of the refuge traveling at high speeds. Erecting barriers or placing barrels around pedestrian refuges for added protection was a suggested solution; also, the construction of pedestrian overpasses in areas with high pedestrian volumes was a common request.

- *Lane Boundaries and Curb Lines*—Many comments centered on the need for increased conspicuity of lane lines, curbs, medians, and raised channelization at intersections. Painted curbs and curbs that are "gradually rounded" or sloped, rather than vertical, were generally preferred.

- *Intersection Corner Obstructions (Sight Distance)*—Difficulty seeing intersecting traffic, as well as pedestrians, because of parked vehicles, signs, or structures too near the corner was reported. Cutting the sidewalk on a diagonal at the corner to increase visibility was a suggested solution.

- *Other Features*—Several geometries that are not frequently encountered, but which nevertheless pose special problems, were identified by these group participants—in particular, traffic circles and five-leg intersections. Traffic circles were characterized as confusing and dangerous, with difficulties maneuvering into and out of this feature attributed most often to the excessive speed of other traffic. For five-leg intersections, pedestrian crossing problems resulted from the fact that three separate crossings are typically required to negotiate such facilities.

PRELIMINARY LABORATORY STUDY

Of the 81 individuals who participated in the focus group discussions, 60 individuals were invited to take part in a Preliminary Laboratory Study to obtain more in-depth understanding of older driver and pedestrian difficulties with specific problem intersection geometric features cited in the previous effort. The study methodology relied upon a structured interview format to obtain categorical and rating-scale data describing older road users' preferences for design alternatives, where a target geometric element was presented in contrasting configurations using 35mm slides of real-world intersection scenes taken from the driver's perspective.

The geometric elements examined in this study depicted the following seven features encountered at intersections:

(A) Varying angle at which one (two-lane) roadway intersects another at a skewed junction (either T or four-way).
(B) Varying radius of corner curb cuts.
(C) Varying offset distance for opposite left-turn lanes at an intersection.
(D) Varying angle experienced by merging traffic at the gore of an auxiliary right-turn lane with an intersecting roadway.
(E) Varying elevation of prohibited driving areas upstream of left-turn storage bays (includes crosshatched median islands as well as different raised channelization treatments).
(F) Varying elevation of prohibited driving areas separating an auxiliary right-turn lane from through lane(s).
(G) Varying distance downstream from an intersection of a lane drop for through traffic (lanes merge across intersection).

Sample Selection

A rigorous sample selection procedure was undertaken in this study to characterize the representativeness of the present test subjects with respect to relevant functional capabilities, and to permit selection of test samples for later studies in this project whose sensory/perceptual, cognitive, and motor response capabilities were already well-documented. Prospective subjects were recruited as described previously in the focus group methodology. Overall, two older driver age categories were sampled equally: (1) "young-old" individuals, ages 65-74, and (2) "old-old" persons, age 75 and older. The sample demographics are reported in Table 4.

The young-old and old-old samples in this study were tested for static visual acuity, contrast sensitivity, useful field of view, immediate memory capacity (digit span), block design [Wechsler Adult Intelligence Scale-Revised (WAIS-R)], and simple reaction time (RT), using the following measurement techniques. *Binocular static visual acuity* was determined using a Sloan wall chart illuminated diffusely at a level of 90 candelas per square meter (cd/m^2). *Static contrast sensitivity* thresholds were obtained for sine-wave gratings with spatial frequencies of 1.5, 3, 6, 12, and 18 cycles per degree (cpd), using a diffusely illuminated Vistech VCTS 6500 wall chart, and then were scored according to age norms provided by Vistech. Useful field of view (UFOV) was assessed using a model 2000 Vision Attention Analyzer to measure the detection, localization, and identification of suprathreshold targets in complex displays;

performance was scored according to the percent reduction in functional capability on three subtests—processing speed, divided attention, and selective attention—and also in terms of a composite measure of UFOV reduction. *Immediate memory capacity* was assessed using the forward and backward digit span tests in the WAIS-R battery; recall scores reflect the number of consecutive digits accurately repeated following auditory presentation of digit sequences monaurally over headphones, with performance of both young-old and old-old age groups then compared against the WAIS-R standardization sample. The ability to reason, analyze spatial relationships, and integrate visual and motor functions was tested using the *block design subtest of the WAIS-R* battery, where the time to arrange nine blocks into a pattern provided by the experimenter was the performance measure of interest. Finally, each subject's *simple reaction time (RT)* was measured, and reported as the average of the five central latencies out of seven button-push responses to a visual stimulus on a computer display.

Table 4. Characteristics of participants in the preliminary laboratory study.

Age Group	Number of Subjects	Number of Males	Number of Females	Age Range	Mean Age	Median Age
Young-Old	30	15	15	65-74	69	68
Old-Old	30	8	22	75-86	80	79

The extensive testing of prospective subjects outlined above provided thorough knowledge of the pool from which the sample of older participants in the later, larger scale laboratory investigation would be drawn, and bolstered the generalizability of findings in this problem identification exercise. A complete characterization of the test sample according to these indices is summarized in Tables 5 through 9 and Figures 2 through 6.

Table 5. Measured acuity of test sample.

Age Group	Percent of group with at least 20/40 acuity	Mean Acuity	Range of Acuities
Young-Old	87%	20/29	20/20 - 20/60
Old-Old	77%	20/37	20/20 - 20/120
All	82%	20/33.25	20/20 - 20/120

Table 6. Percent of subjects performing below the Vistech established norms for contrast sensitivity, by age group and spatial frequency.

Age Group	Spatial Frequency				
	1.5	3.0	6.0	12.0	18.0
Young-Old	27%	10%	40%	27%	17%
Old-Old	27%	10%	63%	30%	23%

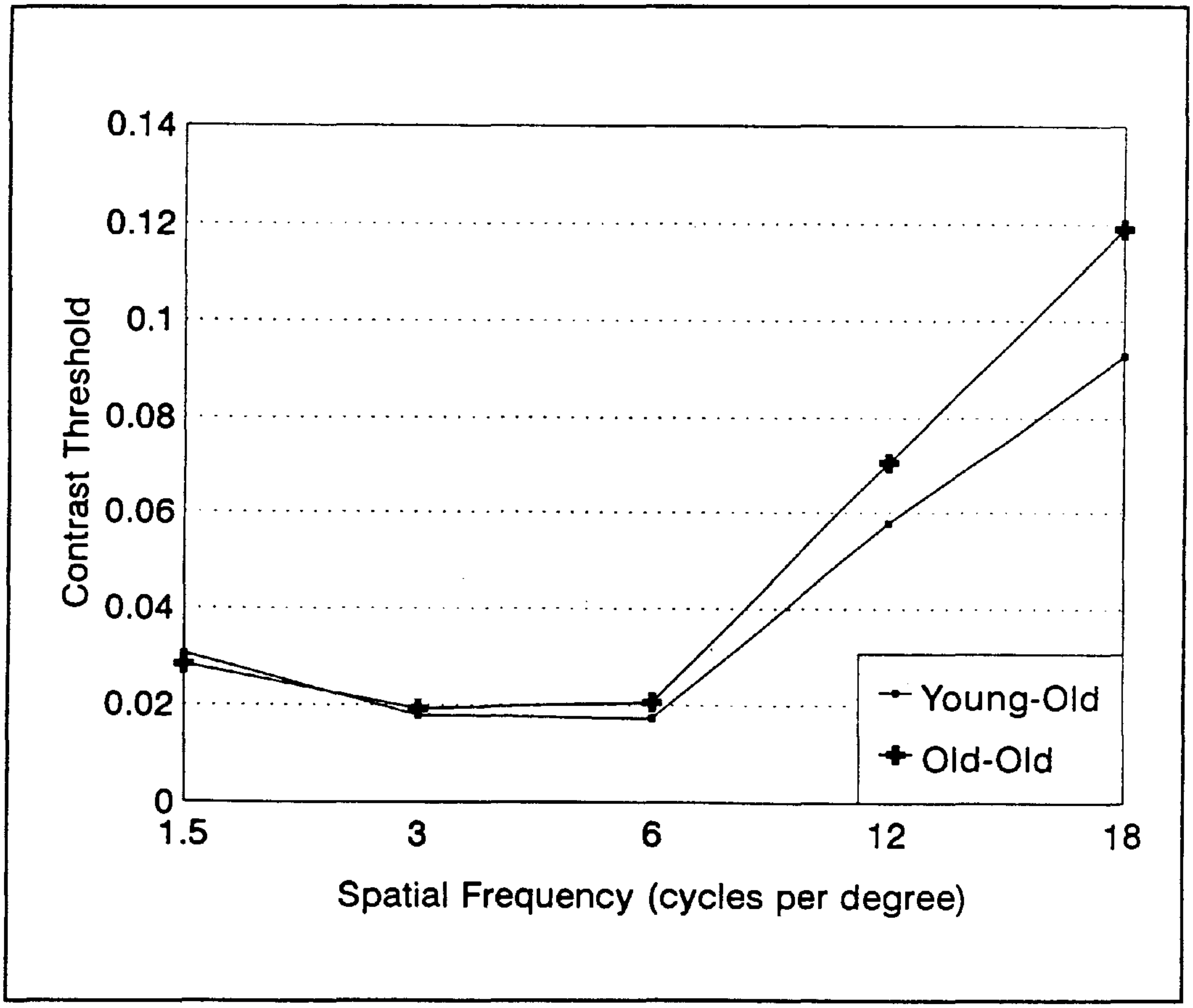


Figure 2. Mean contrast thresholds of laboratory study sample, by spatial frequency.

Table 7. Measured reductions in useful field of view, by age group and type of deficit.

Age Group	Processing Speed Deficit			Divided Attention Deficit			Selective Attention Deficit			Composite UFOV Reduction (%)	
	% of group with no deficit	% reduction for subjects showing deficit		% of group with no deficit	% reduction for subjects showing deficit		% of group with no deficit	% reduction for subjects showing deficit			
		$\bar{x}$	Range		$\bar{x}$	Range		$\bar{x}$	Range	$\bar{x}$	Range
Young-Old	81.5	13	5-20	55.5	6	5-15	0	24	17.5-30	29	17.5-50
Old-Old	72.4	14	5-30	31.0	14	5-30	0	26	5-30	40	17.5-85
All	76.8	14	5-30	42.8	11	5-30	0	25	5-30	34.5	17.5-85

Table 8. Digit Span test results, by age group.

Age Group	Forward Digit Span			Reverse Digit Span		
	Mean No. of Digits Reported	Std. Dev.	Range	Mean No. of Digits Reported	Std. Dev.	Range
Young-Old	6.2	1.11	3-8	4.67	1.11	3-8
Old-Old	5.9	0.94	4-9	4.6	1.02	3-7
All	6.05	1.04	3-9	4.63	1.06	3-8

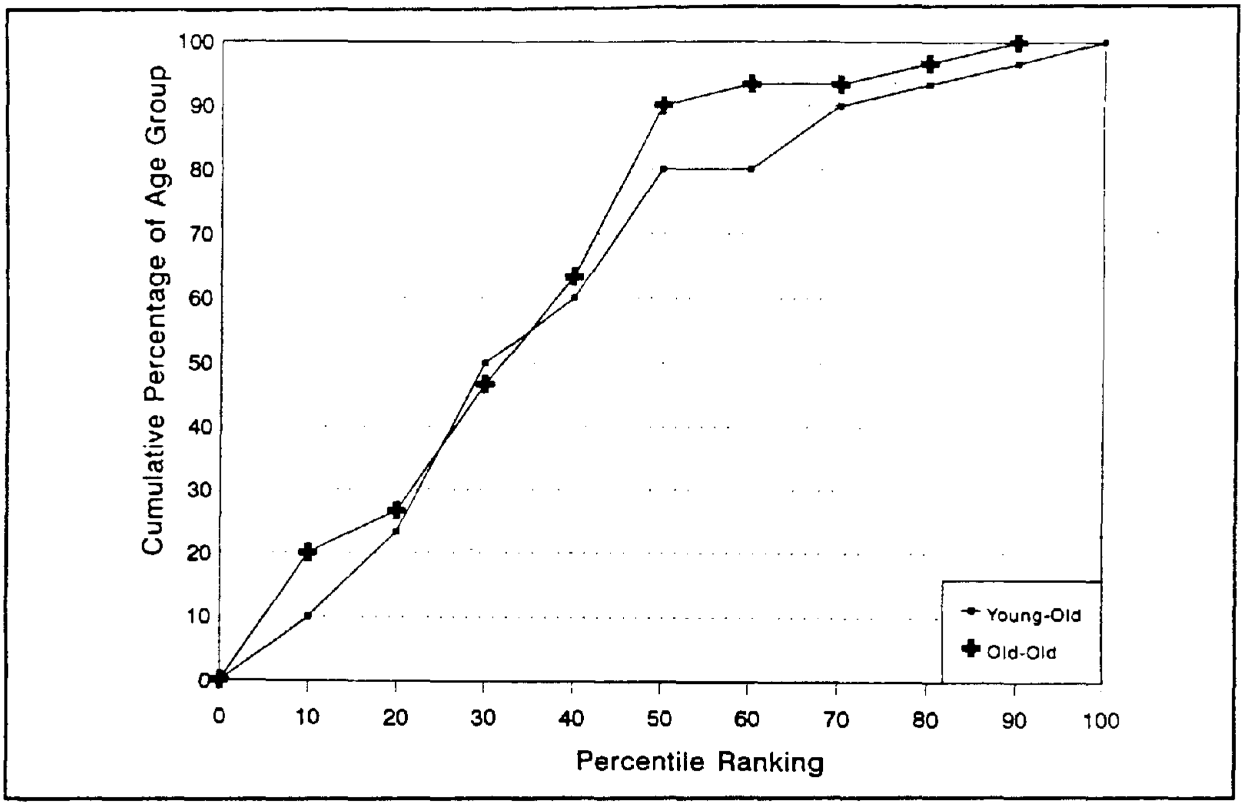


Figure 3. WAIS-R Digit Span test performance in relation to the standardization sample.

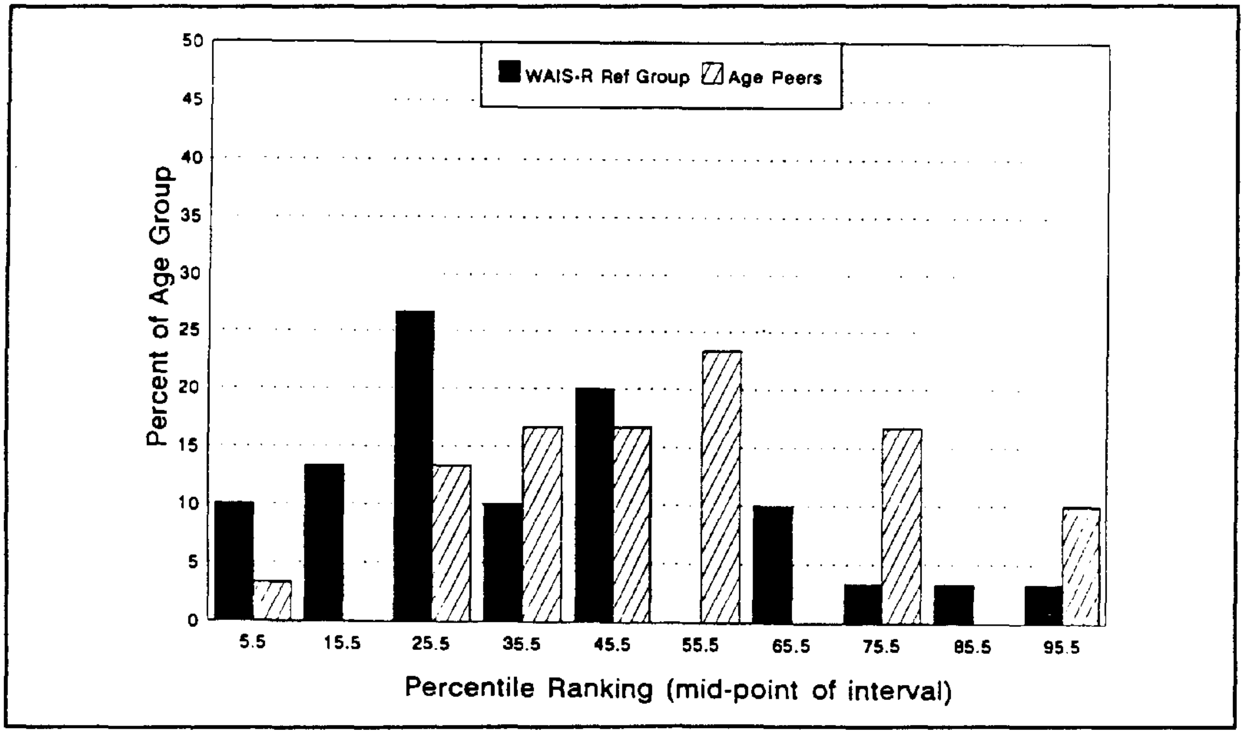


Figure 4. Young-old digit span performance in relation to cited comparison groups.

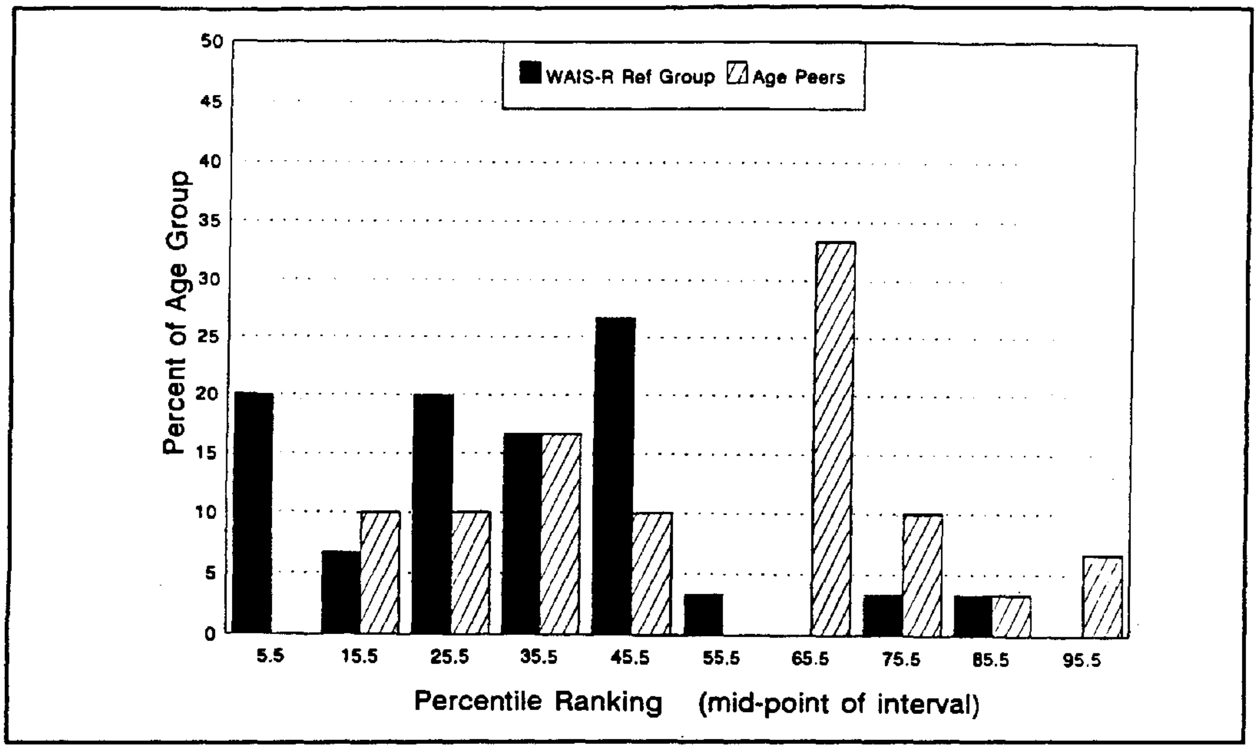


Figure 5. Old-old digit span performance in relation to cited comparison groups.

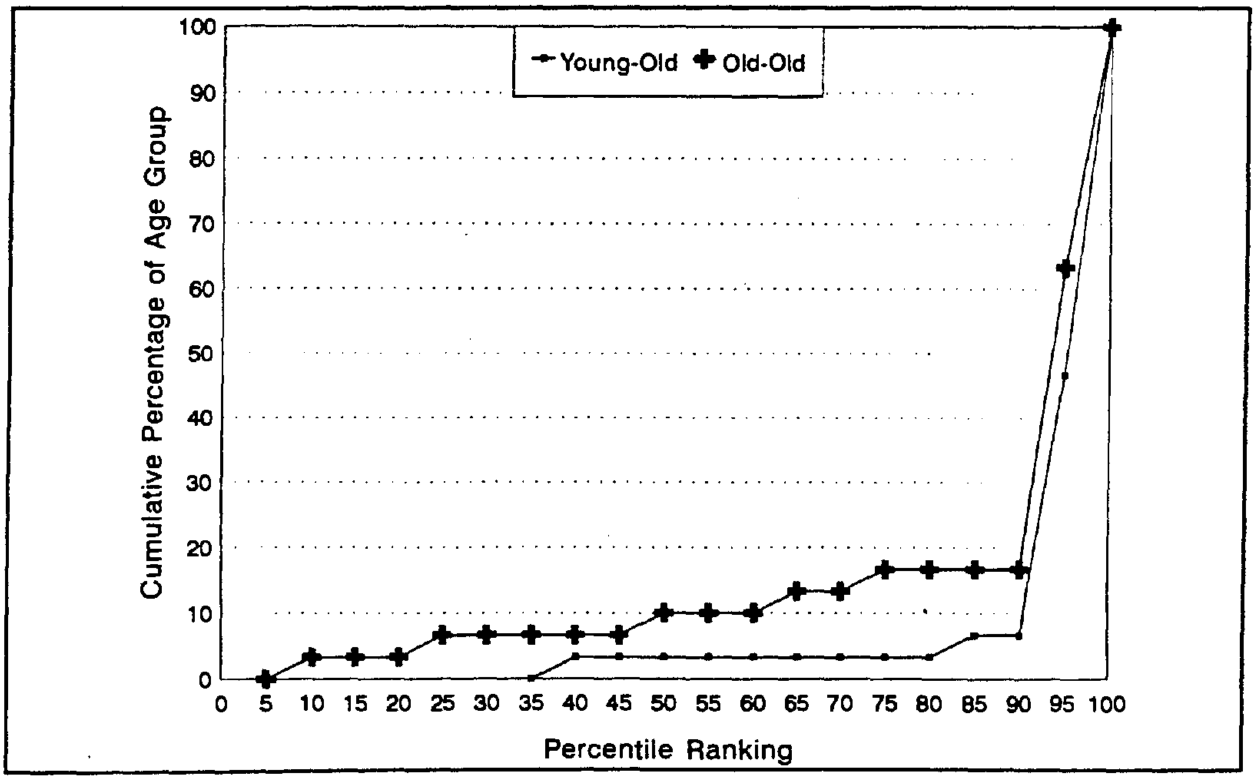


Figure 6. WAIS-R Block Design test results in relation to the standardization sample.

Table 9. Measured (simple) reaction time, by age group.

Age Group	Reaction Time (ms)	
	Mean	Standard Deviation
Young-Old	288.66	39.7
Old-Old	301.23	57.2
All Older	294.95	49.6

Data Collection Methodology

Preference ratings by older road users for alternative geometric elements were the focus of this data collection effort. The data collection protocol used a series of 35mm slides to show animated approaches to each alternative intersection design element tested to improve the contextual cues available to the subject. Specifically, as the present sample of 60 subjects (30 young-old and 30 old-old) visited the laboratory one at a time for data collection, each older road user was shown slides of intersections illustrating variability in the target feature. The various target features identified in the list at the beginning of this section included: (A) varying angle at which two roadways intersect; (B) varying radius of corner curb cuts; (C) varying offset distance for opposite left-turn lanes at an intersection; (D) varying angle experienced by merging traffic at the gore of an auxiliary right-turn lane with an intersecting roadway; (E) varying elevation of prohibited driving areas upstream of left-turn storage bays; (F) varying elevation of prohibited driving areas separating an auxiliary right-turn lane from through lane(s); and (G) varying distance downstream from an intersection, where a lane for through traffic is eliminated (lanes merge across intersection). These same designations are maintained in describing the results of the preliminary laboratory study.

The study began for each subject with the experimenter explaining the purpose of the laboratory study. The seven geometric features were then studied separately; i.e., the alternative configurations for the various elements were not intermixed during data collection, resulting in seven blocks of trials for the laboratory study, with three to five alternatives—consisting of one to four slides each—displayed within any given block. The experimenter told the participant how many alternatives he/she would be comparing for each feature and how many slides he/she would see during the approach to the intersection being evaluated before the experimenter showed the first slide. Then, the approach was shown by manually controlling a slide projector, with the experimenter pausing to describe critical elements in each scene and to answer any questions the subject asked to aid him/her in acquiring the perspective required to compare alternatives shown for a particular feature. This resulted in an exposure duration of approximately 10 s per slide, with a 15-s duration for the final slide in the approach. This strategy was adopted to help focus the subjects' attention on the feature of interest and was justified because the protocol did not seek to test sensory or perceptual factors, but instead emphasized older subjects' evaluative responses for contrasting design options. After each design option was shown, the subject was allowed to review any slides about which he/she had questions, and, as an additional memory prompt, all subjects were presented with a "reminder" slide which best illustrated the design alternative shown in each sequence (usually the last slide in each approach) before performing the preference ratings.

After the multiple alternatives for a given block were presented, the experimenter asked each subject to select his/her preferred design in terms of the alternative that seemed to be the safest or easiest to use, or which in some other way best met his/her needs in that situation. Then, the subject was asked to evaluate how much better the preferred alternative was than the other choices. A paper-and-pencil rating scale from 0 to 100 was used, with a value of 100 always assigned to the preferred alternative. The subject verbally reported to the experimenter which alternative was the best, and the experimenter entered the code for this alternative on the rating scale at the 100 mark. The subject then looked at the rating scale and told the experimenter where on the scale to place each of the remaining design options, to indicate his/her **relative** evaluations of each other alternative shown. For each alternative, the subject was required to give the experimenter a specific score on the rating scale.

Finally, each participant was asked to explain in his/her own words the reasons for his/her preference of a particular alternative for each intersection feature shown in the slide presentation. These responses were recorded, and any comments about needed improvements for a given feature were also noted on the data collection form. Data collection lasted from 1 to 1-1/2 hours per subject; upon completion, a $25 payment was provided to each study participant.

Results and Discussion

Results were tabulated separately for each age group, for each of the seven geometric features evaluated in this study. For every geometric feature studied, descriptive statistics showing the frequency and percentage of responses with which each alternative design received a particular ranking were summarized, and were then used to prepare histograms, allowing visual inspection of these data. These histograms are presented following the discussion of results for each feature examined in this study, in each case, depicting the percent of the sample ranking a given alternative first (best), second, etc. In addition, subjects' reasons for choosing a particular alternative as their preference are reported in the following discussion.

Feature A: Angle at Which Two Roadways Meet. Figure 7 depicts the four alternatives evaluated and Figure 8 presents the percent by rank for each alternative. As indicated in Figure 8, both older samples preferred Alternative 4 for this feature, in which a skewed intersection has been realigned such that a 90° junction is permitted. Sixty percent of the 65- to 74-year-old sample and 47 percent of the age 75+ sample preferred this design option and the level of agreement concerning the ranking of Alternative 4 was consistently better than for other alternatives at every possible position in the rank order.

The most common reason given for this preference by individuals in both the young-old and old-old samples was that it is easiest to see traffic coming from both the left and right at a right-angle intersection, because the required head turn is not extreme in either direction. This response mirrors the findings of the focus group discussions on this topic, and underscores the importance of this age-related physical limitation as a potential source of problems in intersection use by older drivers.

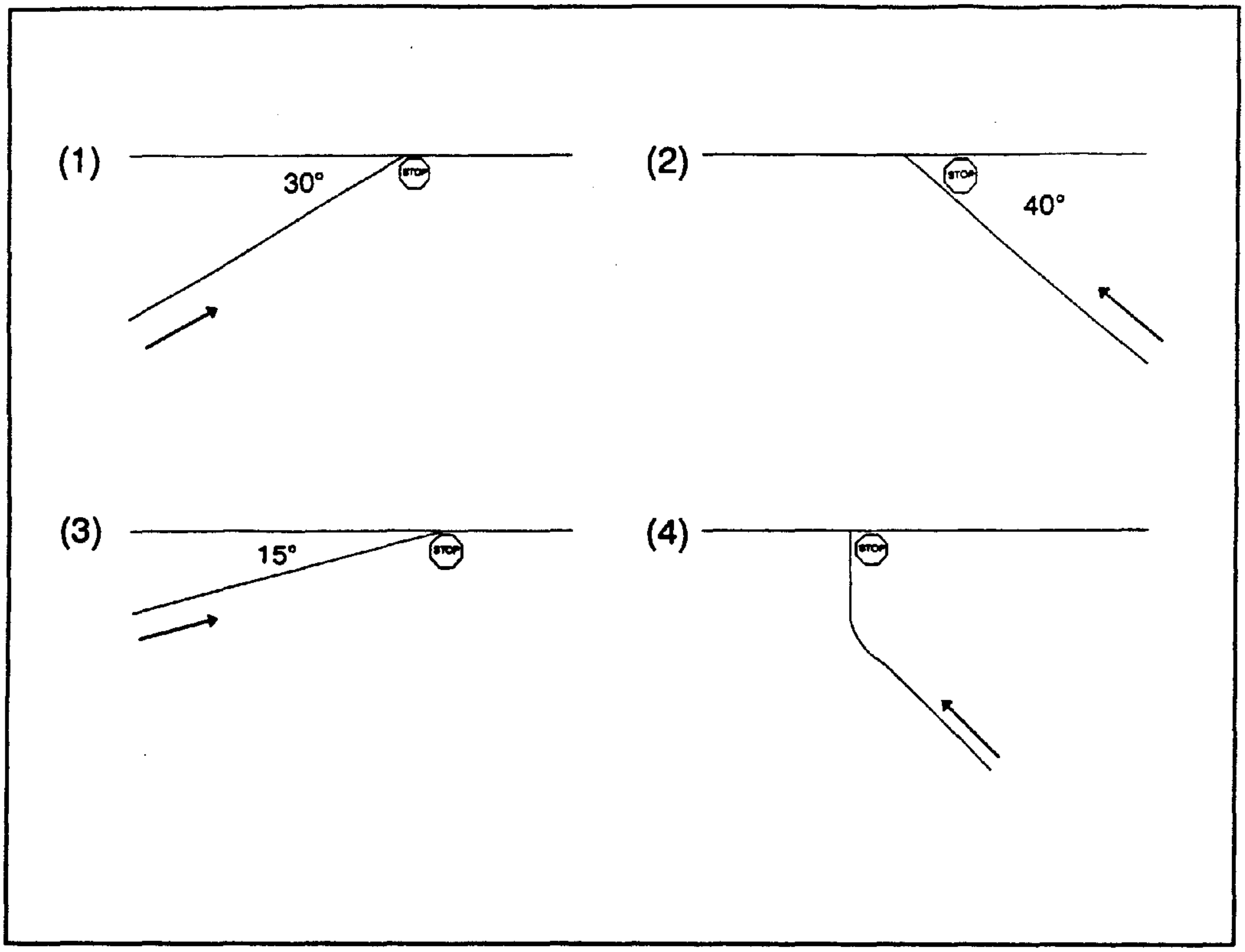


Figure 7. Feature A: angle at which two roadways meet.

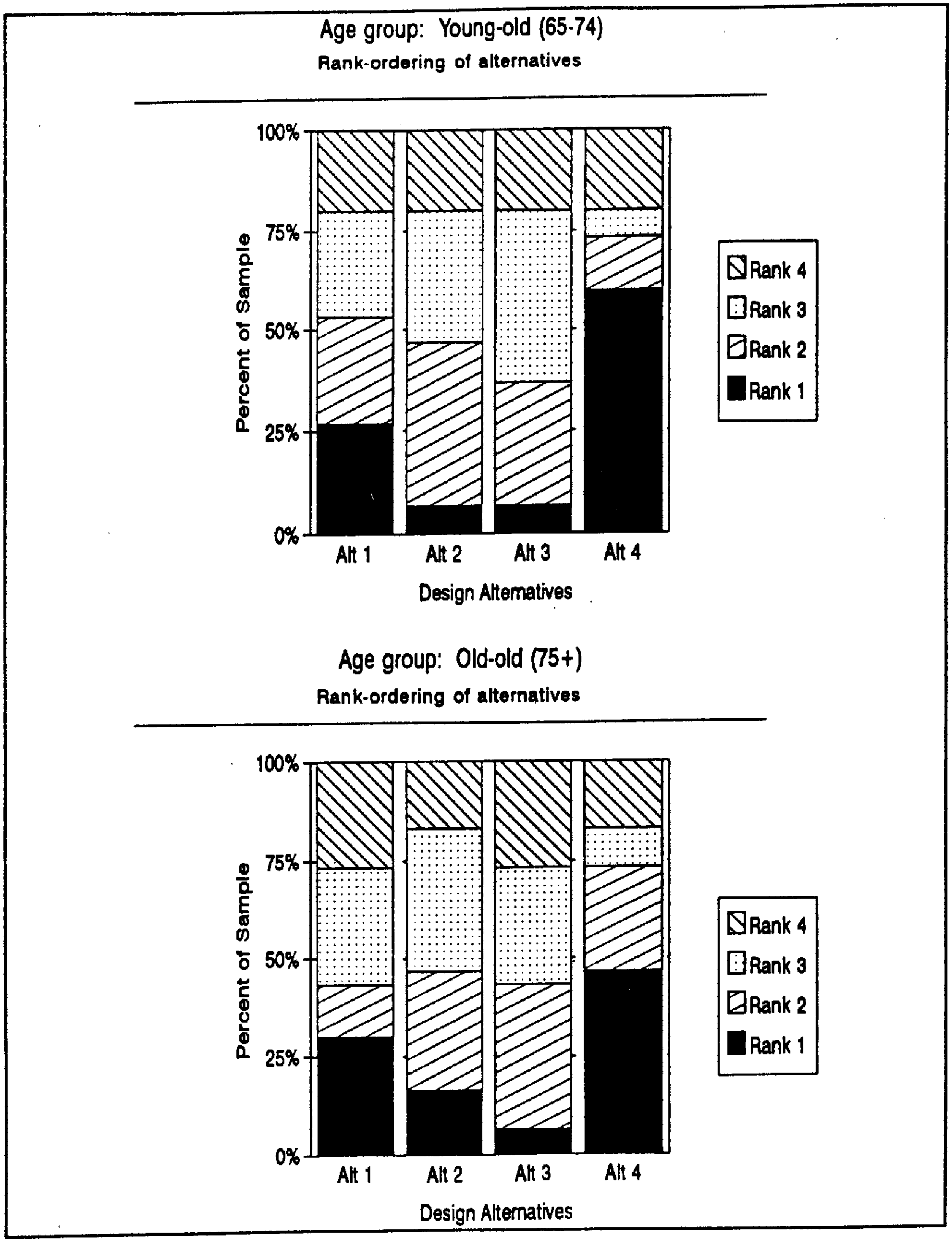


Figure 8. Percent-by-rank display of young-old and old-old subjects' preferences for Feature A alternatives.

Feature B: Radius for Corner Curb Lines. Figure 9 depicts the four alternatives evaluated and Figure 10 presents the percent by rank for each alternative. Figure 10 indicates that there was an identical ranking of alternatives among both older samples for this feature: Alternative 3 was consistently preferred, followed by Alternative 4, based on the rankings of "most preferred" and "second most preferred." Alternatives 1 and 2 faired rather equally overall; however, Alternative 1 most often was ranked fourth (least preferred) by subjects, while Alternative 2 was more often ranked third. Driver's *most* preferred design option was described by a broadly rounded corner with a circular radius of 14.6 m (48 ft), while the *least* preferred design option was a corner with only a 5.5-m (18 ft) radius.

The clear pattern of responses indicating a first-second preference order for a broadly rounded curb line, followed by a truncated corner curb cut, can be explained according to the comments provided for this feature. Apparently, both young-old and old-old drivers in this study are most concerned about ease of turning, citing the better maneuverability and less chance of hitting the curb as their primary basis of response. The second most common, but also strongly weighted, reason for the preference responses of both groups related to the degree of visibility of traffic on intersecting roadways. Alternatives 3 and 4 both are described by corner curb-line geometries offering ease of turning and good visibility; isolated responses to the truncated corner geometry (Alternative 4) indicated concern that ***too much*** room in the right-turn path might result in a lack of needed guidance information and could lead to a maneuver error, however, and that it could be harder to detect pedestrians with this design.

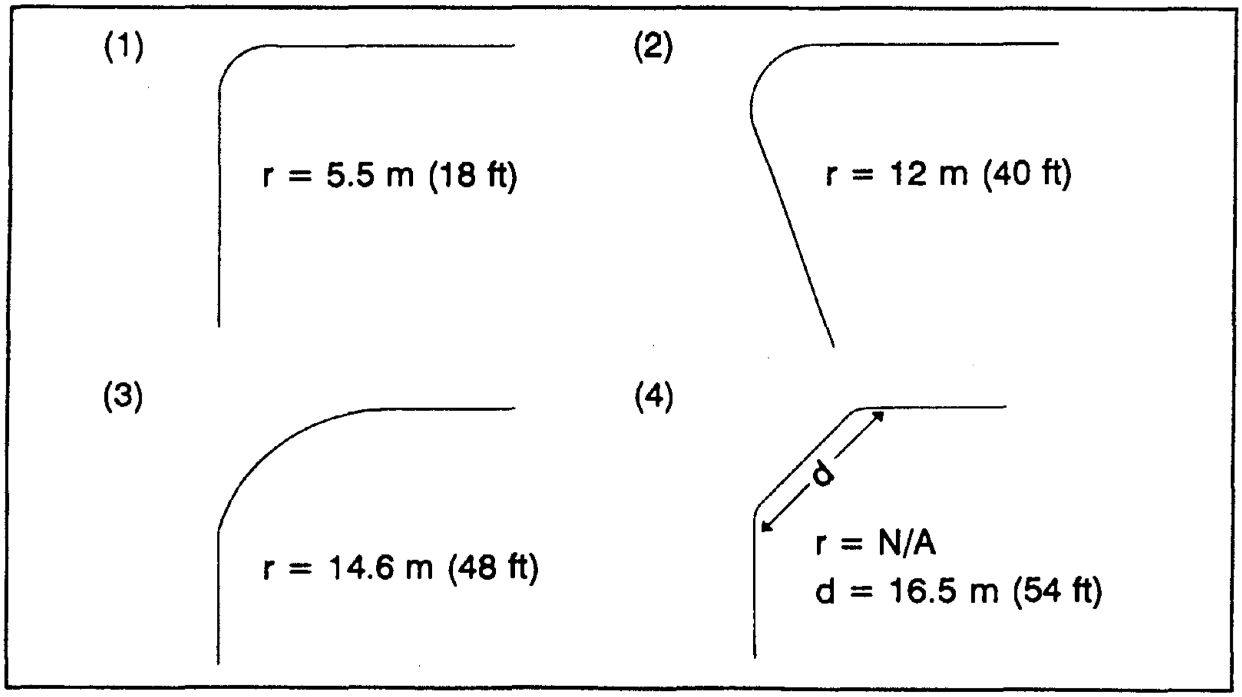


Figure 9. Feature B: radius for corner curb lines.

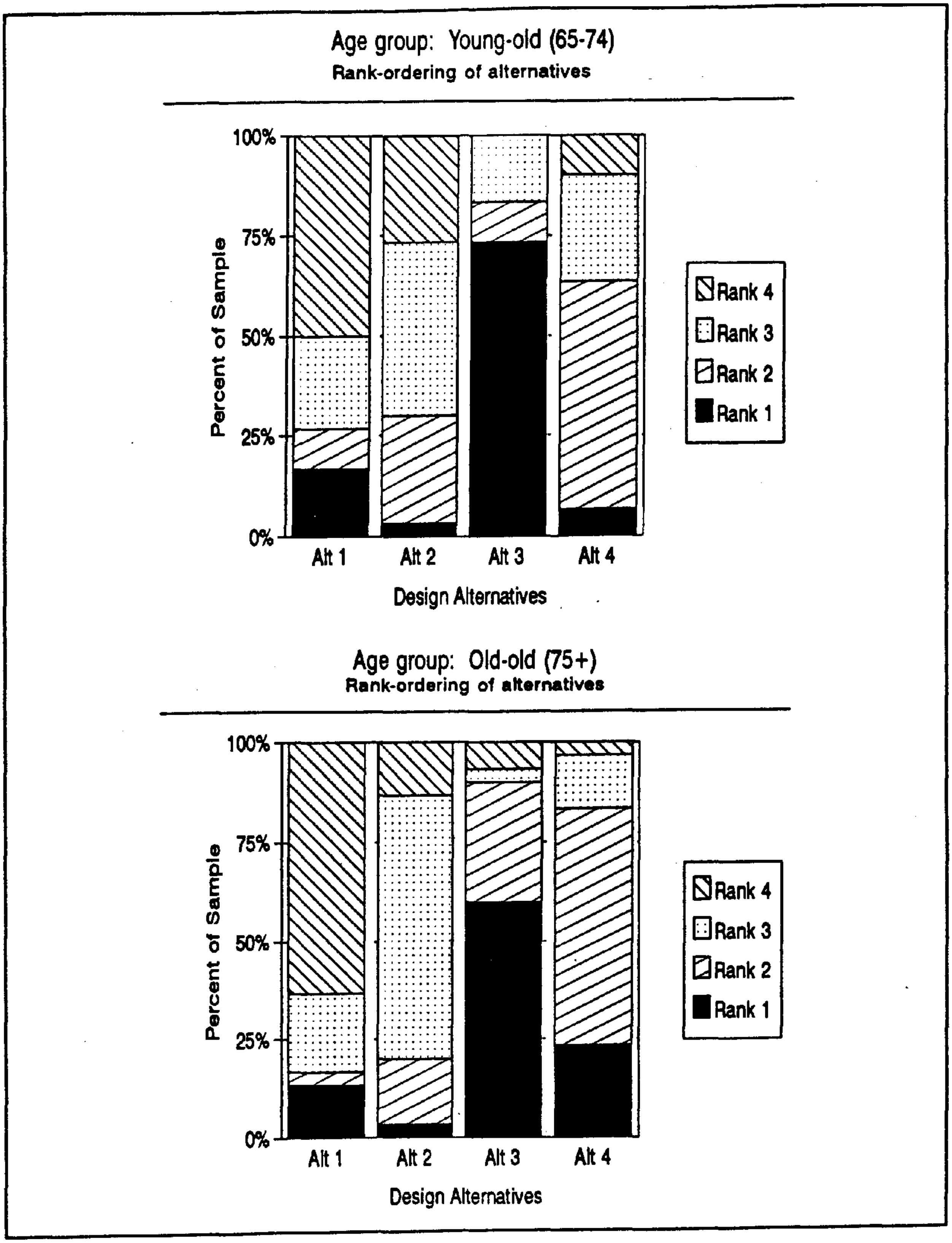


Figure 10. Percent-by-rank display of young-old and old-old subjects' preferences for Feature B alternatives.

Feature C: Offset Distance for Opposite Left-Turn Lanes. Figure 11 depicts the four alternatives evaluated and Figure 12 presents the percent by rank for each alternative. Strong agreement among the 65-74 and 75+ age groups as to the design options for this feature is indicated by the data summarized in Figure 12, with the channelized aligned geometry (Alternative 4) overwhelmingly preferred and the fully aligned, non-channelized opposite left-turn lane geometry (Alternative 3) as the second most preferred design. The full negative offset geometry (Alternative 1) was ranked as the best design *least* often and as the worst design *most* often.

The reasons for the selection of Alternative 4 as the preferred design are numerous. In decreasing frequency of mention, both the old-old and young-old respondents recognized the enhanced safety of: (1) having the left-turn lane separated from all other traffic by physical barriers; (2) having improved visibility to detect oncoming (through) traffic; (3) eliminating the possibility of a tentative left-turner changing his/her mind and cutting in front of through traffic at the last minute to go straight, or of someone in the through lane cutting in front of a left-turner; (4) removing uncertainty for everyone negotiating an intersection of what drivers in the left-turn lanes are going to do; and (5) providing conspicuous visual cues (i.e., the median barrier) for the left-turn lane during the intersection approach.

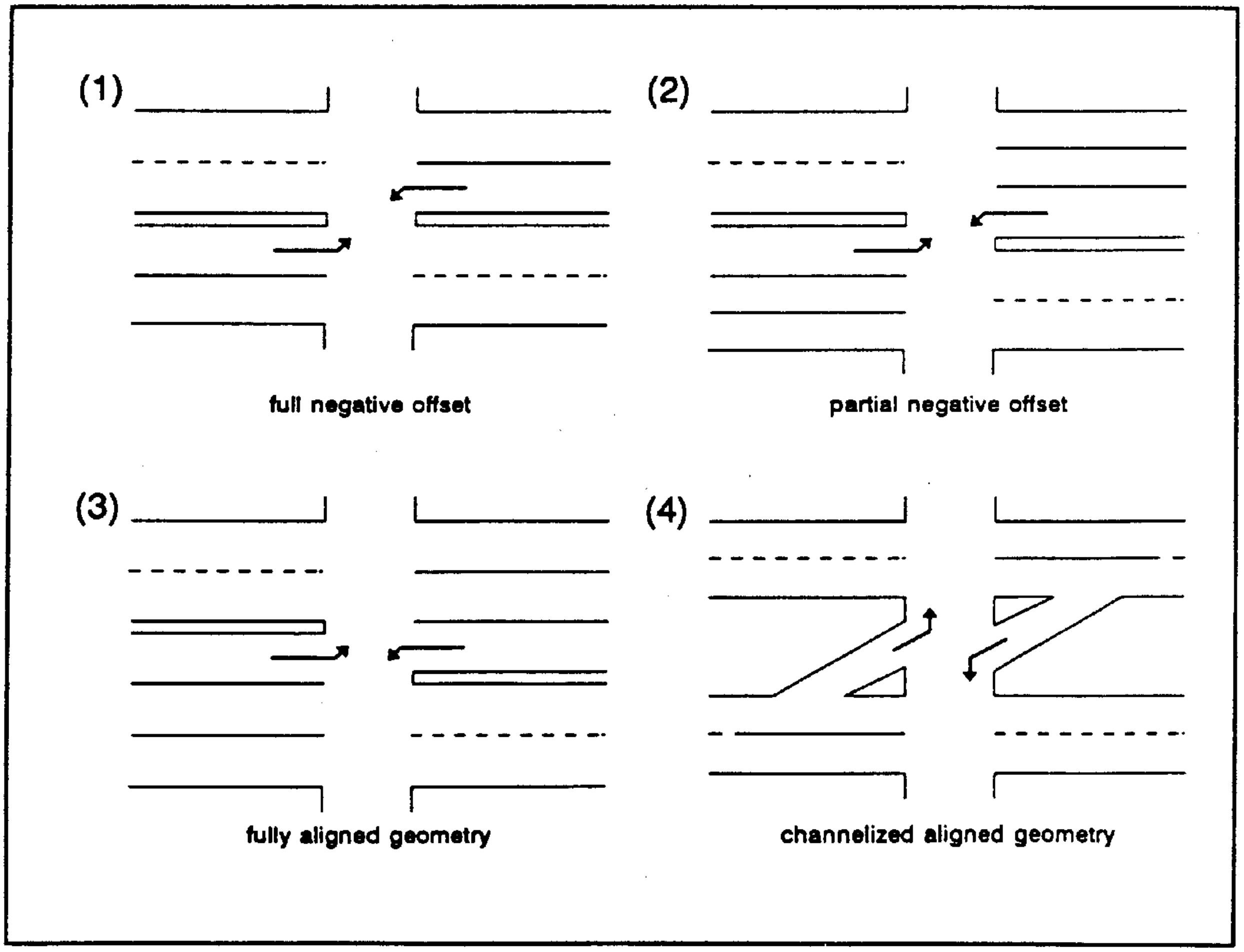


Figure 11. Feature C: offset distance for opposite left-turn lanes.

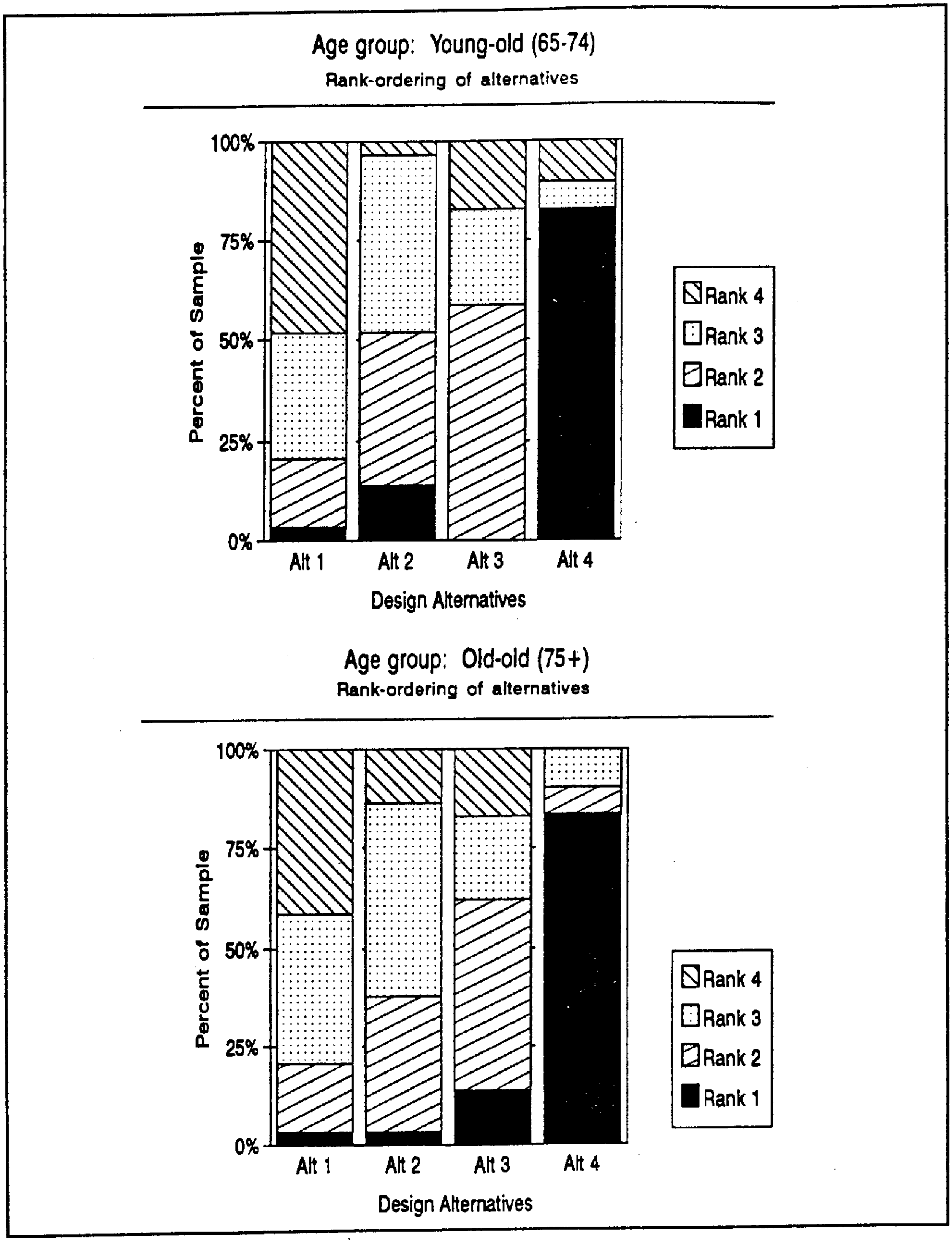


Figure 12. Percent-by-rank display of young-old and old-old subjects' preferences for Feature C alternatives.

Feature D: Right-Turn Geometry and Operational Alternatives. These alternatives included both channelized and non-channelized right-turning operations, where the turning driver also enters the intersecting roadway at varying angles for some alternatives versus others, as shown in Figure 13. As indicated by the data summarized in Figure 14, 65- to 74-year-old and age 75+ subjects preferred the design option described by a channelized auxiliary turn lane meeting the intersecting roadway at an angle of approximately 20° (Alternative 2). This was not an overwhelming choice among the present samples, however. The old-old group preferred Alternative 4 nearly as often as Alternative 2; in Alternative 4, a right-turning driver makes a non-channelized turn at a 90° angle into an acceleration lane. With the young-old group, this design option (Alternative 4) was less often preferred, receiving the highest ranking with roughly the same frequency as Alternative 1 (a 90° angle turn without an acceleration lane). Furthermore, the acceleration lane design received the highest frequency of rank 4 (*least* preferred) responses by the 65-74 age group drivers. The strongest cluster of unfavorable (rank 3 or rank 4) responses were made by both older driver groups for Alternative 3, described by a channelized auxiliary turn lane meeting the intersecting roadway at approximately 45°.

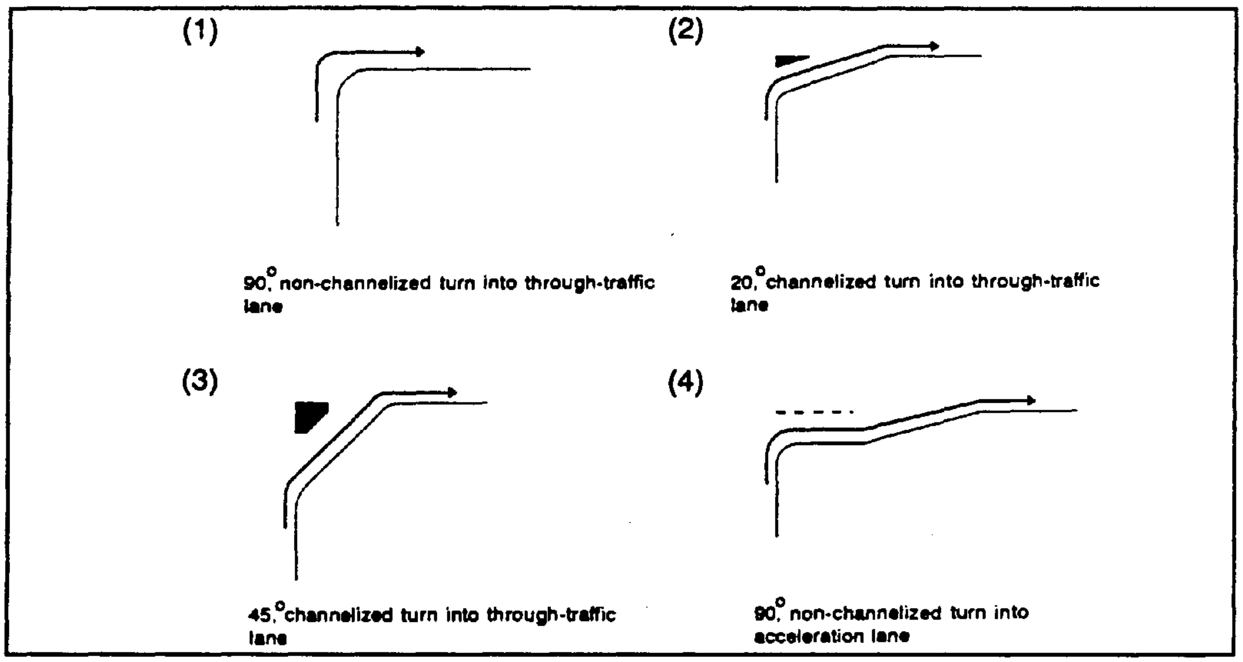


Figure 13. Feature D: right-turn lane geometry and operations.

Reasons for subjects' stated preferences among these alternatives were diverse. Individuals preferring the 90° angle turn (without acceleration lane) cited its simplicity; the certainty about where to stop before entering the intersecting traffic stream; and most importantly, the ease of turning the head to check oncoming traffic to the left. Those who preferred the acceleration lane design believe it is more safe to come up to speed before entering the intersecting traffic stream, with the added benefit of not having to immediately pull in front of other drivers to make the turn; the most common reservation about this design was that the drivers don't like to change lanes, and are aware of the danger of blind spots as they rely on mirror vision to make a lane-change maneuver in this situation. Finally, reasons for selecting the most preferred design, Alternative 2, included the ease of the turning angle (approximately 20°), and the good view of traffic approaching from the left using the driver's side mirror ***while still being protected by the channelizing island.***

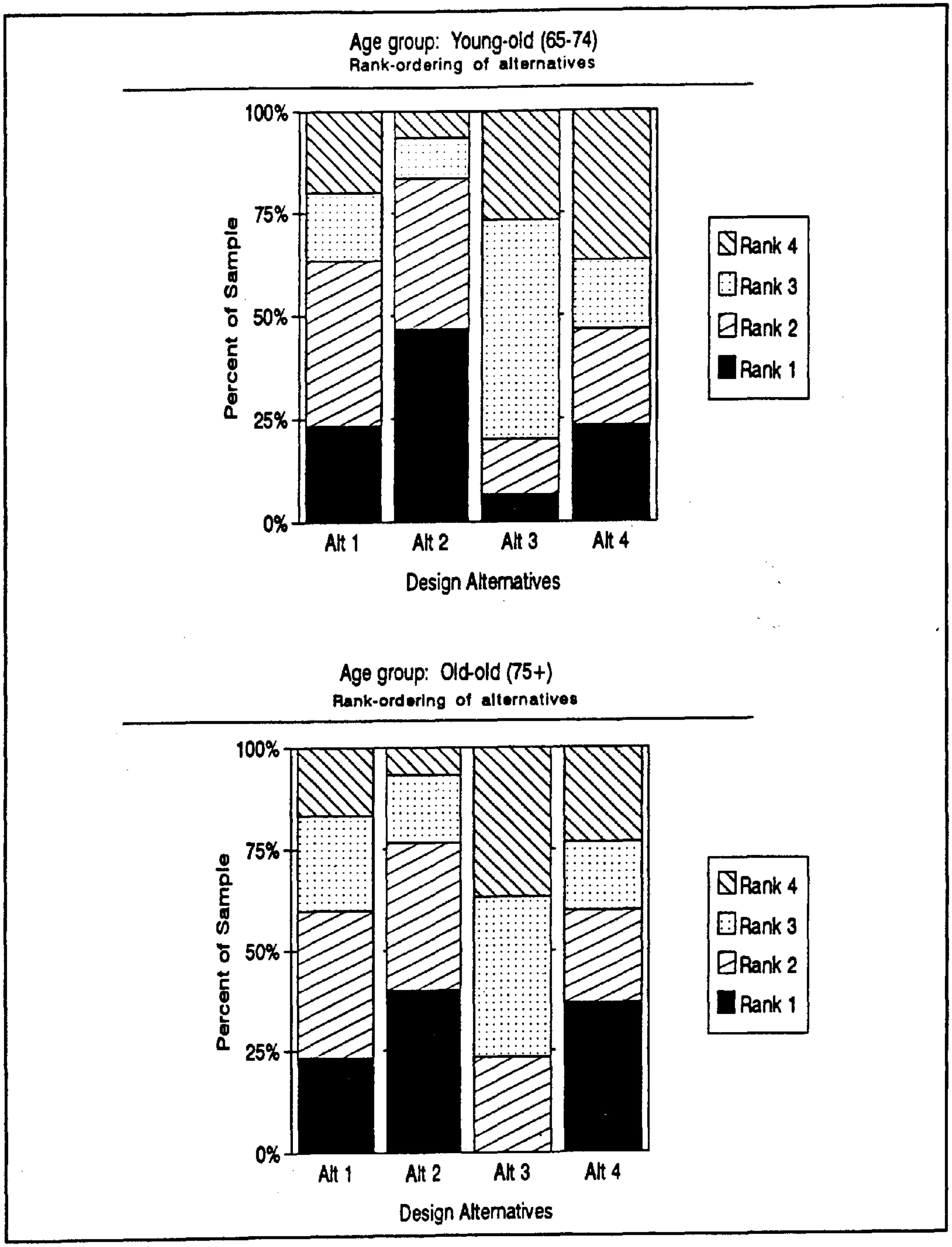


Figure 14. Percent-by-rank display of young-old and old-old subjects' preferences for Feature D alternatives.

Feature E: Varying Left-Turn Storage Bay Median Characteristics. Five alternatives were evaluated for this feature, as shown in Figure 15. Data summarized in Figure 16 indicate that the two designs with elevated medians (Alternatives 4 and 5) were most often preferred; the two designs with crosshatched pavement markings (Alternatives 1 and 2) were less preferred; and a median with a "washboard" raised pavement treatment (Alternative 3) was regarded favorably by 65- to 74-year-old drivers, but not by subjects in the age 75+ sample. Overall, however, there was no single alternative consistently preferred by a wide margin by either age group, as drivers were able to identify strengths and weaknesses for all design options.

For painted markings, a longer median (upstream of the turn bay) was universally ranked higher than a short median crosshatched area; while drivers liked the convenience of being able to drive over the markings to get into the turning lane if through traffic backs up at the intersection, they also acknowledged the danger posed to them when other drivers do the same thing, and complained about poor visibility when the paint is worn or when driving under rain/snow conditions. Both older driver samples cited superior visibility and safety when selecting raised concrete medians as their preferred design option, also noting that such designs provide desirable pedestrian refuges. At the same time, favorable comments about raised features were consistently accompanied by emphasis on the importance of painted curb lines and the use of reflectors on the upstream edge of median islands to avoid collisions with this intersection feature. Young-old drivers preferred sloping curbs on raised concrete medians, while old-old drivers preferred vertical (15.2-cm [6-in]) curbs. Interestingly, while the "washboard" design was not most often preferred by either age group sampled in this study, its perceived liabilities were limited to those shared by pavement markings (poor visibility at night and during adverse weather conditions); its perceived strengths included: (1) "it keeps people off the median, but will not damage your car if you drive on it by accident," (2) "it's possible to drive on this feature in an emergency, but it's respected more than painted lines," (3) "it provides good auditory and vibration cues that you are driving where you're not supposed to," and (4) "it's more conspicuous than paint."

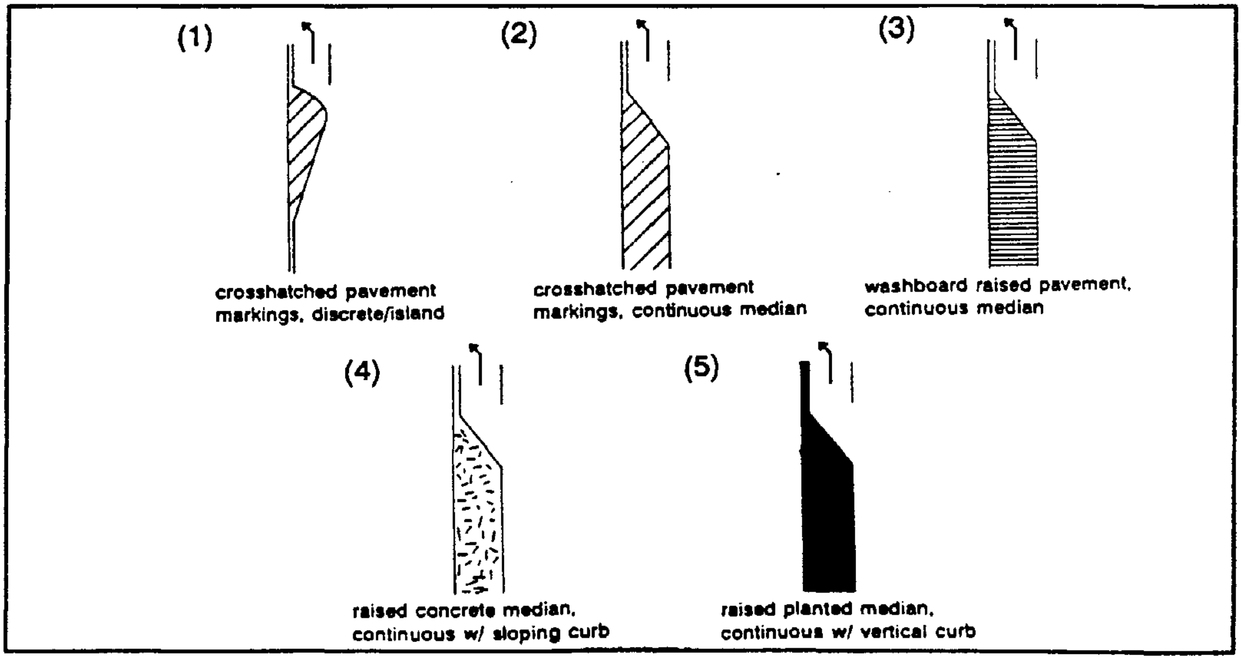


Figure 15. Feature E: left-turn storage bay median characteristics.

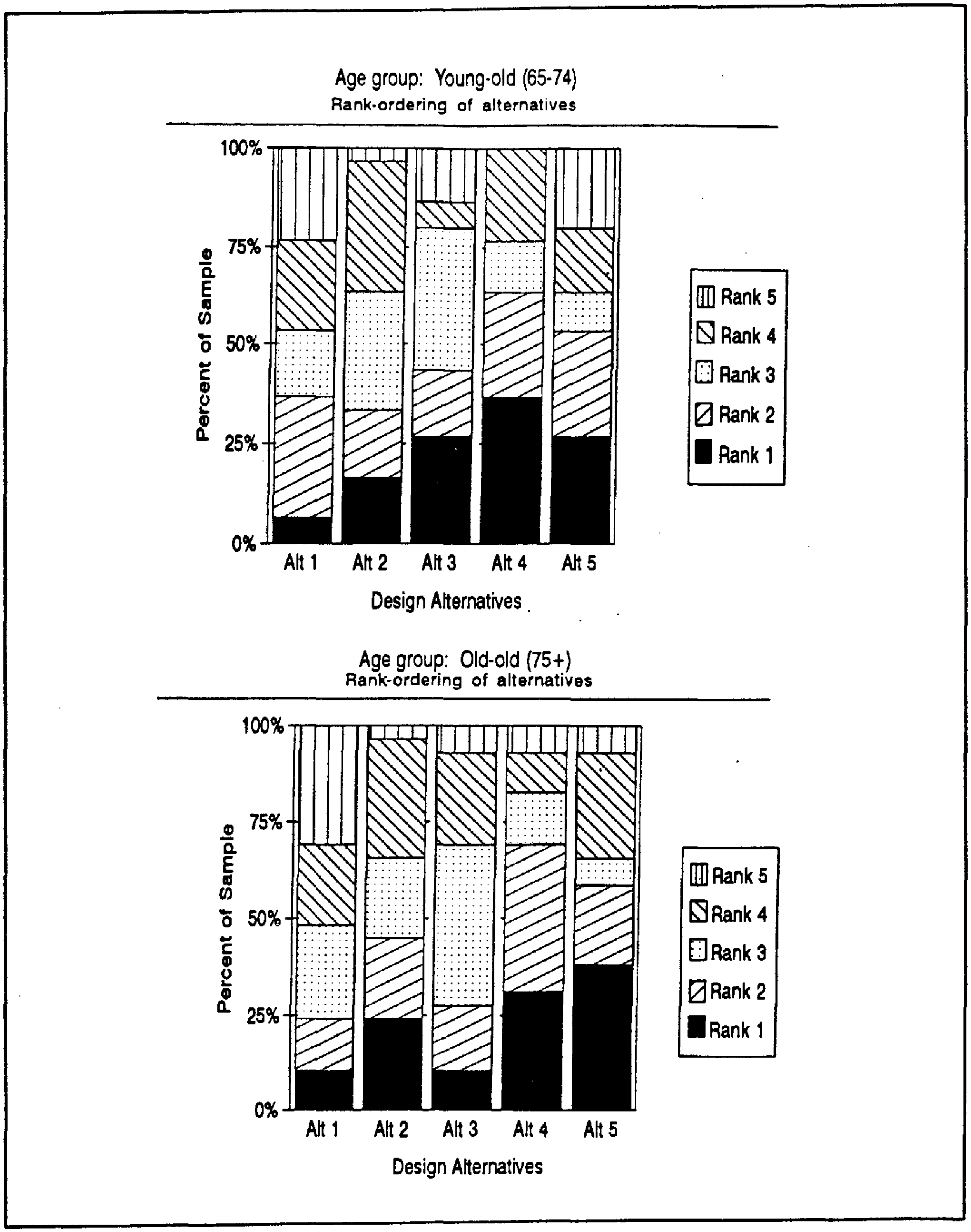
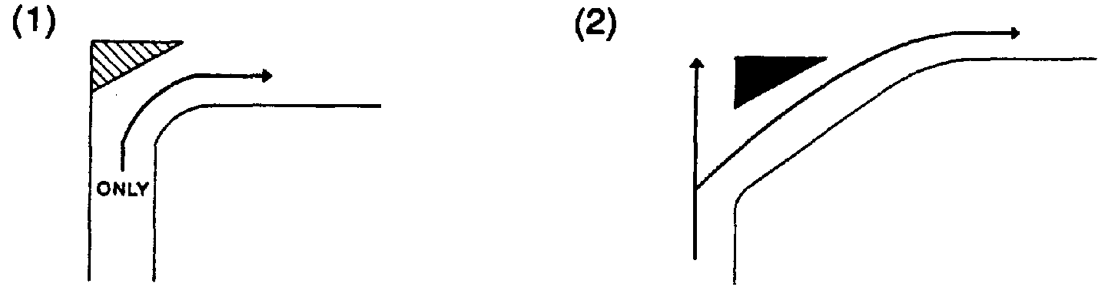


Figure 16. Percent-by-rank display of young-old and old-old subjects' preferences for Feature E alternatives.

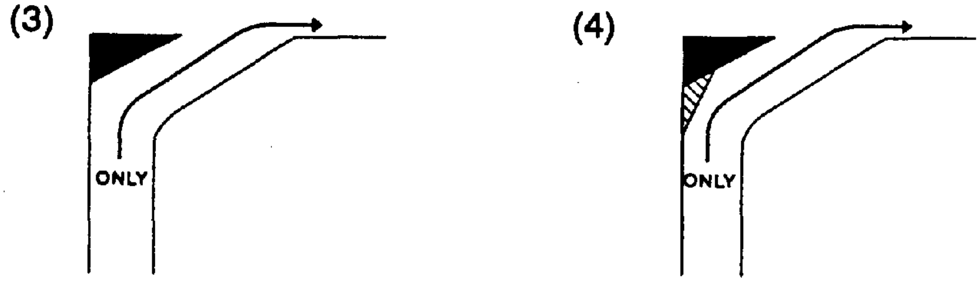
Feature (F): Right-Turn Channelization Alternatives. Figure 17 depicts the four alternatives evaluated and Figure 18 presents the percent by rank for each alternative. Clearly, there is very strong agreement between the young-old and old-old drivers sampled concerning the rank order of alternative design options, from most preferred—Alternative 4, an island with vertical curb, plus upstream crosshatching—to least preferred. Receiving nearly equivalent *low* rankings as most preferred were designs with crosshatched pavement markings only and islands with vertical curbs (but no crosshatching); the "island with sloping curb" option consistently elicited an intermediate number of most preferred responses.

As indicated by the sample's comments regarding this intersection feature, both the protection to the turning driver of a physical barrier from through traffic *and* the improved visibility of the barrier figured prominently as reasons for preferring Alternative 4. Protection for pedestrians was again noted, as in the case of median island channelization for left turns, but to a substantially lesser extent than the driver protection and feature visibility issues. Furthermore, it may be inferred by looking at the preferences at the lower rankings that concerns over driver protection for this sample marginally outweigh feature visibility. The "crosshatched markings only" treatment was most often least preferred; and, between the two designs with raised channelization only, islands with sloping curbs were preferred to those with vertical curbs.



crosshatched white pavement markings only

raised concrete island w/ sloping curb



raised concrete island w/ vertical curb

raised concrete island w/ vertical curb fronted by crosshatched white pavement markings

Figure 17. Feature F: right-turn channelization treatments.

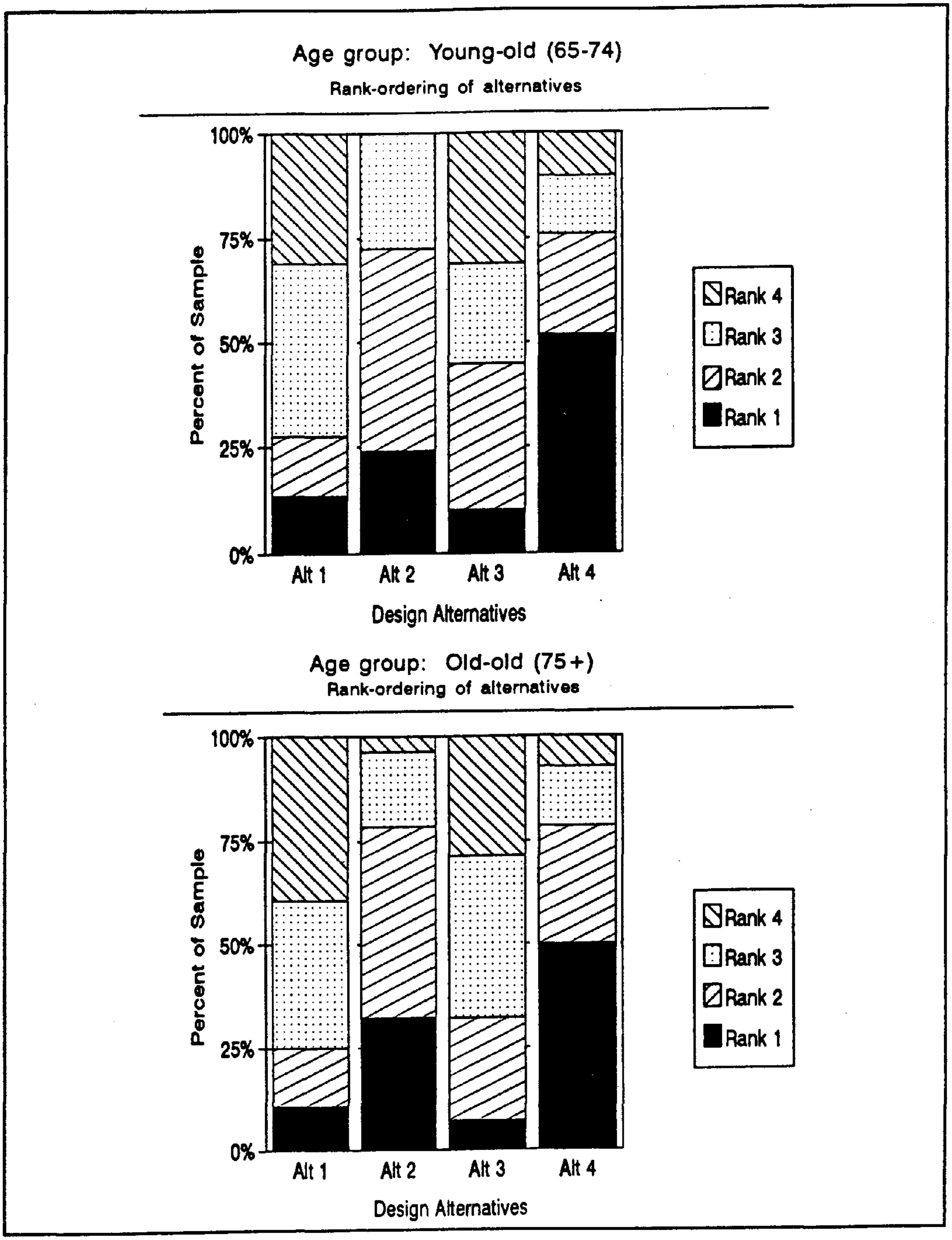


Figure 18. Percent-by-rank display of young-old and old-old subjects' preferences for Feature F alternatives.

Feature G: Varying Distance to Lane Drop Across Intersection. Figure 19 depicts the three alternatives evaluated and Figure 20 presents the percent by rank for each alternative. For this feature, the young-old and old-old study participants were unanimous—not surprisingly, among three alternatives where pavement-width reductions occurred at increasing distance across an intersection (39.6 m [130 ft], 114 m [375 ft], and 182.9 m [600 ft]), the farthest distance was overwhelmingly the most preferred design, the middle distance nearly always ranked second, and the shortest distance ranked last. In each case, the options presented to subjects depicted two lanes of through traffic being channeled into one lane downstream of the intersection, as shown in Figure 19.

The reasons cited by study participants for their responses to these alternatives are interesting in relation to the specific operational and design elements examined here and, more generally, in relation to information processing and maneuver decision-making problems experienced by older drivers. First, the overall slowing of perceptual/cognitive functions associated with increasing age is consistent with subjects' emphasis on the need for more space (and time) for finding an acceptable gap to merge into. An explicit benefit of the added space and time provided by Alternative 3 derives from drivers' early comprehension of operational requirements from information on advance warning signs that aid response preparation. Also, physical factors are implicated in the subjects' preference for this alternative, in the drivers' stated reliance on the outside rearview mirror for sampling of adjacent-lane traffic (i.e., instead of head turns to the rear).

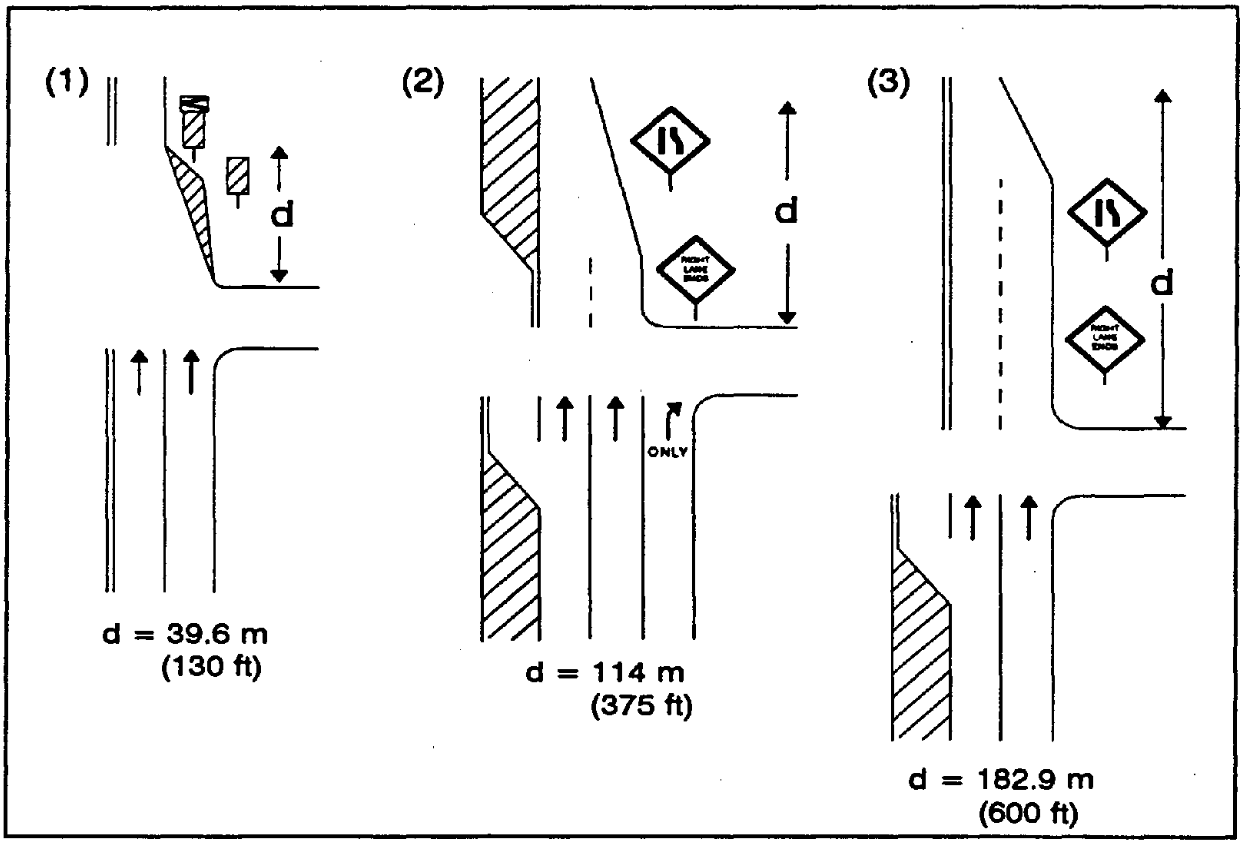


Figure 19. Feature G: distance to lane drop across intersection.

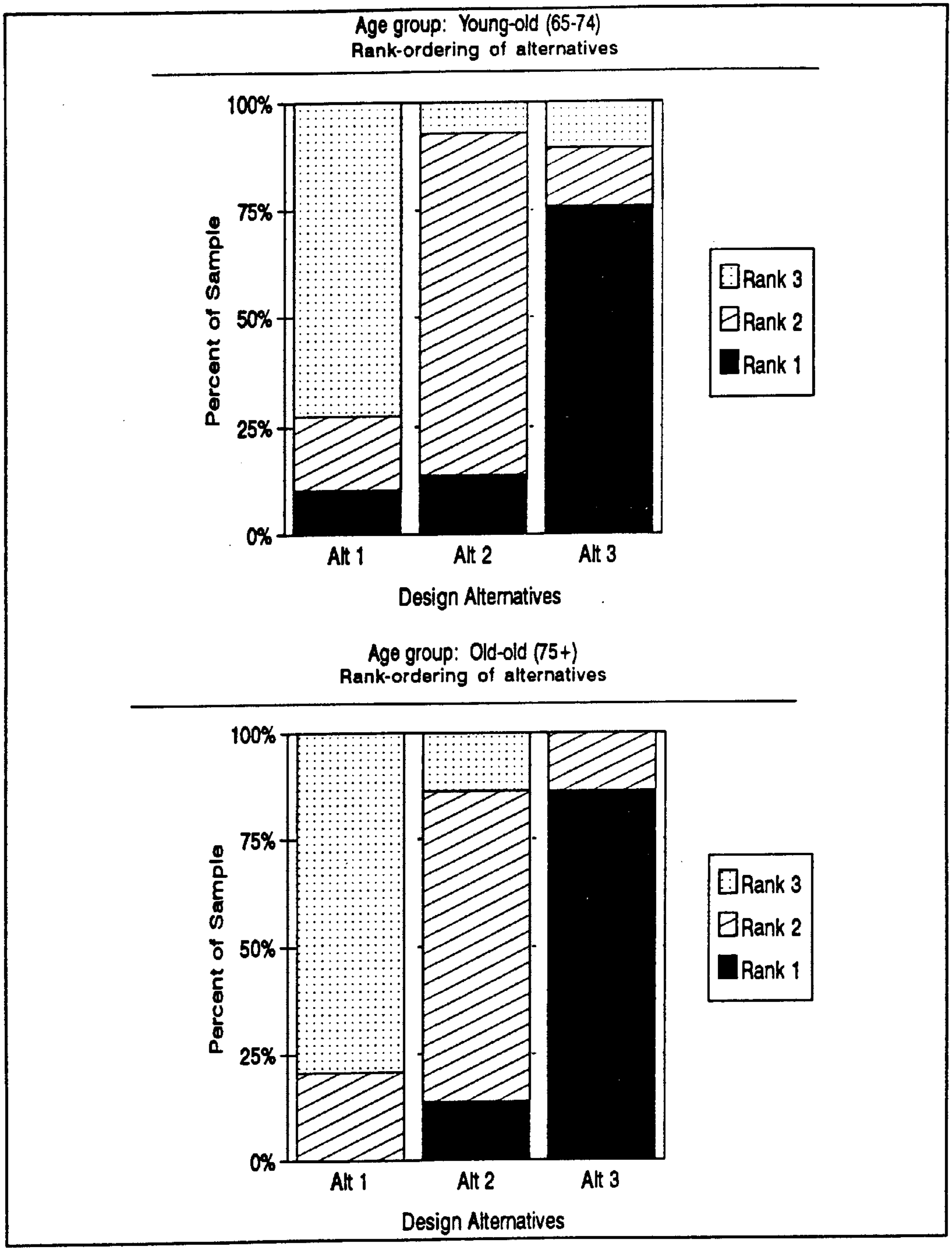


Figure 20. Percent-by-rank display of young-old and old-old subjects' preferences for Feature G alternatives.

Suggestions for design improvements further underscored older drivers' needs for advance information to minimize potential conflicts by more effectively responding to the lane-change task demands associated with this feature. In stressing the need for placement of redundant warning signs farther upstream of the lane-drop location, some individuals wanted such messages posted on the near-side of the intersection. In fact, right-turn-only operations to force drivers to merge into one through lane *before* reaching an intersection were deemed preferable to downstream pavement-width transitions where extended merging zones cannot be provided. A desire was also expressed for more cues—for example, different colors of pavement—to mark the "last merge point," where the shoulder lane actually ends. The age differences documented in the literature review argue that it is relatively more important for older drivers to know how far they can travel in the (shoulder) lane before being forced to merge to the left in this situation.

PRELIMINARY FIELD STUDY

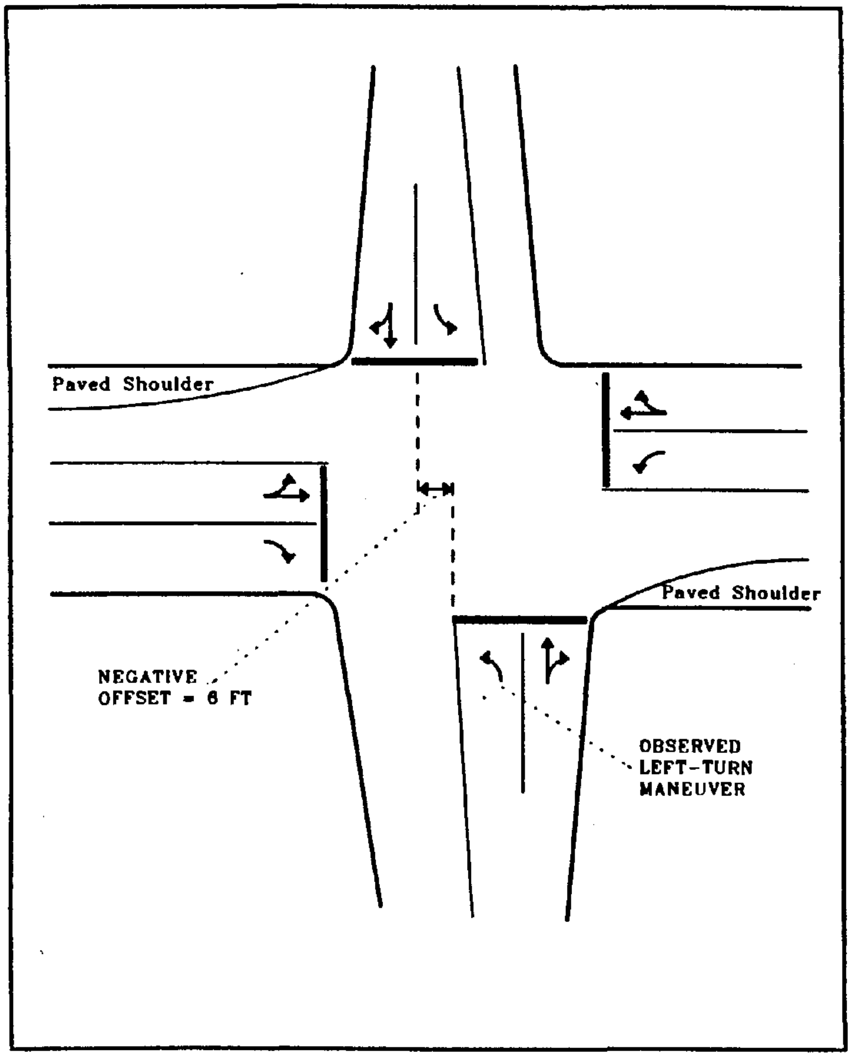
Exploratory field studies were conducted in this project activity in an effort to confirm and amplify age differences noted in previous tasks—namely, that older drivers experience difficulty and make errors in the performance of both right-turning and left-turning movements at intersections, particularly as the turning driver. Observational study procedures and results are reported below for two different geometric designs within each of the two scenarios selected for the preliminary field studies: a right-turn and a left-turn situation.

Left-Turn Maneuver Observations

Procedures. Two intersections in the suburban Philadelphia, PA area were selected for observation of left-turning maneuvers. As illustrated in Figures 21 and 22, respectively, these locations at Elm Street/Broad Street and Byberry Road/Philmont Avenue contained aligned versus negatively offset opposite left-turn lane geometries. These locations were matched approximately in terms of average daily traffic (ADT) volume; in addition, both locations were signalized, and the left turn of interest occurred only during a permissive green phase, i.e., there was no protective left-turn phase.

Left-turning operations were videotaped to determine how older drivers (age 65+) compare to younger drivers at the two types of left-turn lanes—aligned and negatively offset—in terms of: (1) accepted gap; (2) intersection clearance time; (3) turning path; (4) acceleration profile; (5) number of vehicles in left-turn queue when the left turn was made; and (6) presence and type of vehicle in opposite left-turn bay when the left turn was made. The measures of effectiveness (MOE's) were the mean gap accepted, mean clearance time and speed, mean conflict clearance time, and turning path and acceleration characteristics for each of the age groups (old vs. young) at each type of left-turn scenario (aligned vs. negatively offset).

The data collection effort consisted of videotaping left-turn operations at each of the two sites for more than 6 hours. At the Elm/Broad location, operations were taped from 8:30 a.m. until 4:30 p.m., while at the Byberry/Philmont location, the hours observed were from 8:30 a.m. until 2:30 p.m. The video system consisted of one camera focused on the entire intersection, a time-date generator, a videocassette recorder, a monitor, a microphone system, and other



1 ft = 0.305 m

Figure 21. Byberry Road/Philmont Avenue intersection with offset left-turn lanes.

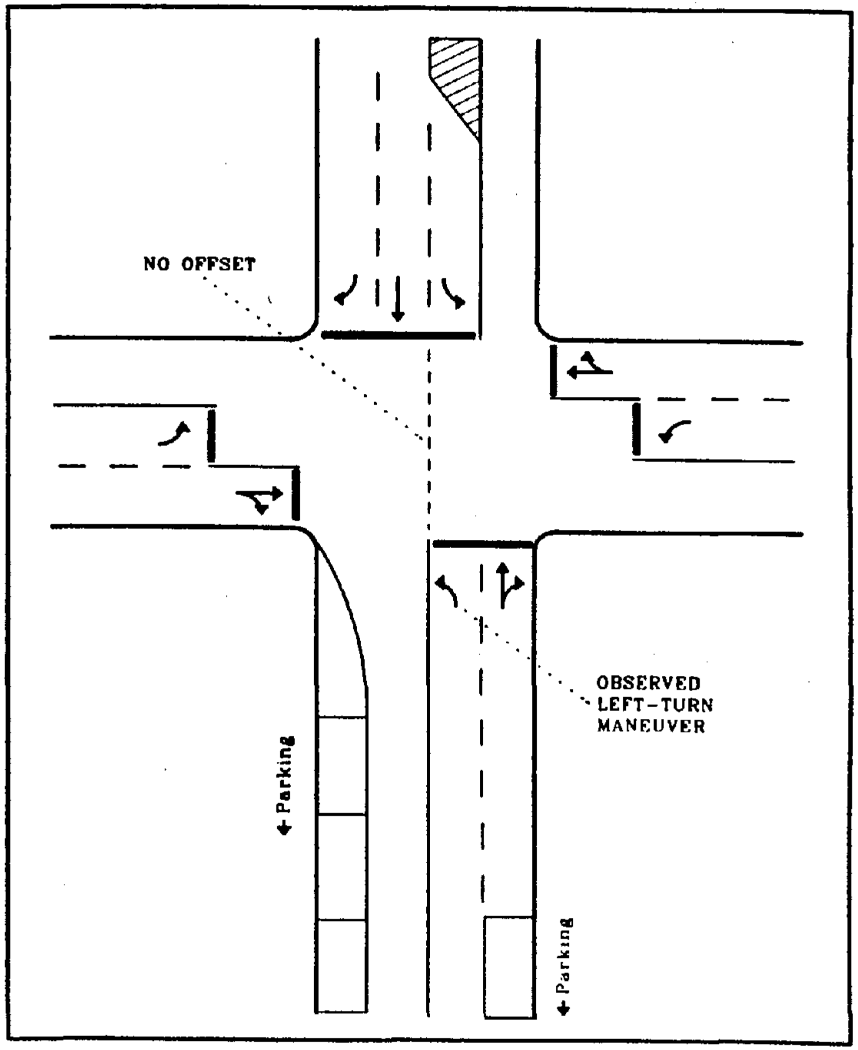


Figure 22. Elm Street/Broad Street intersection with aligned left-turn lanes.

miscellaneous equipment powered from a portable generator. The camera was mounted on a pole attached to the van used for data collection; it provided an adequate view of the intersection and the approaches of interest.

In addition to the video data, manual observations were made of driver age (old vs. young), gender, and license plate numbers for those vehicles of interest. The vehicles that were of interest for this study were those passenger cars that were free-flowing, i.e., traveling far enough behind another vehicle such that they were not influenced by that vehicle. Pickups, vans, minivans, and utility vehicles were not included in the sample due to differences in driver eye height. The license plate numbers were sent to the Bureau of Licensing in Harrisburg, Pennsylvania for information on the age and gender of the vehicle owner in order to confirm the age and gender observations made in the field. The results of this confirmation task resulted in a sample size of only 13 older drivers at the Elm/Broad location and 24 older drivers at the Byberry/Philmont location. A sample size of 50 younger drivers was obtained at each location.

Measures recorded from the videotape for each subject driver included: (1) the "wait time" between the moment a driver arrived at the intersection and the moment the left-turn maneuver was begun; (2) the presence and type (car vs. truck) of vehicle(s) in the opposite left-turn lane at the time the left-turn maneuver was made; (3) the number of vehicles in queue behind the left-turning vehicle at the time the left-turn maneuver was made; (4) the acceleration profile of the left-turning driver during the maneuver, i.e., smooth vs. hesitant or stop-and-go; and (5) the trajectory of the turning path, coded from *1* to *5* as follows: *1* = driver making the left-turn maneuver encroached into the opposing cross-traffic stream; *2, 3, and 4* = drivers properly turning into the cross street from different points within the intersection; and *5* = driver making a left turn from a point that required them to turn more than 90 degrees in order to enter the cross street (see Figure 23).

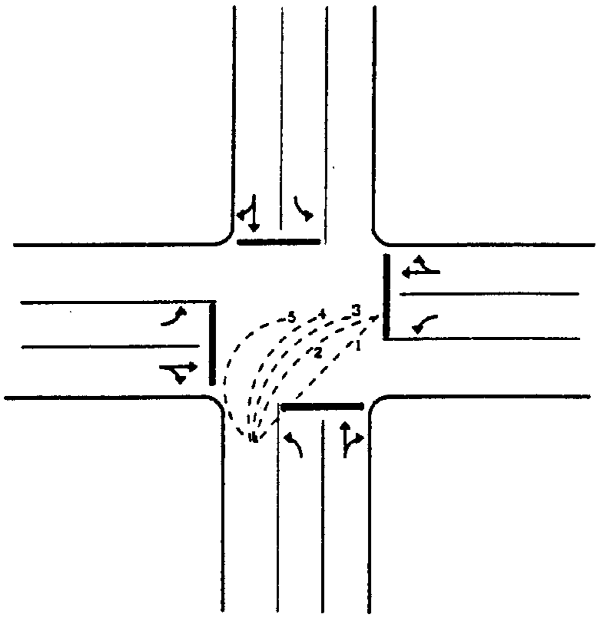


Figure 23. Turning path taken by left-turning vehicle, rated 1 through 5.

All data were entered into a database and the MOE's of interest were produced for each age group and for each left-turn scenario. Data analyses were performed using analysis of variance (ANOVA) for comparing the continuous MOE's (time and speed), while a Fishers Exact Test was used for comparing the frequency data (e.g., number of turning paths). A 95 percent confidence level was selected for determination of significant differences in the statistical tests.

Results. The measured differences between age groups for the variables clearance time and acceleration profile were small and not significantly different from each other at either intersection (aligned or negatively offset left-turn lane geometry). Across all gap scenarios (with and without conflicting vehicles), the older drivers did accept significantly longer gaps than younger drivers at the aligned intersection only. However, further examination of gaps accepted between successive vehicles, i.e., a true gap in the opposing traffic stream, showed no significant differences between driver age groups at either intersection.

One variable that did show significant differences in older and younger driver behavior was turning path. Older drivers encroached into the opposing lane of the cross street when making the left turn more often than did younger drivers at the Elm/Broad location, which was aligned. At the negatively offset intersection, however, there was no significant difference in the turning paths. This result was more likely a result of the throat width on the receiving leg of the intersection as opposed to the left-turn bay alignment. The Elm/Broad location had a throat width of only 3.7 m (12 ft) as opposed to 7 m (23 ft) at the other intersection. This narrow throat width could have resulted in the higher encroachments by older drivers because of a physical difficulty maneuvering their vehicles through smaller areas.

Right-Turn Maneuver Observations

Procedures. Two different intersections in the suburban Philadelphia, PA area were selected for observation of right-turn maneuvers. As illustrated in Figures 24 and 25, respectively, these locations at Street Road/Southampton Estates and York Road/County Line Road contained non-channelized versus channelized right-turn lanes. The first location was a right-turn-only auxiliary lane separated from through traffic only by paint. The second location was a right-turn auxiliary lane separated from the through-traffic stream by a channelizing island. These locations were matched approximately in terms of average daily traffic (ADT) volume.

Right-turn operations were videotaped to determine how older drivers (age 65+) compare to younger drivers at the two types of right-turn lanes—channelized and non-channelized—in terms of: (1) accepted gap; (2) maneuver time; (3) turning path; and (4) number of vehicles in right-turn queue when the right turn was made. The measures of effectiveness (MOE's) were the mean gap accepted, mean maneuver time, and turning-path characteristics for each of the age groups (old vs. young) at each type of right-turn scenario (channelized vs. non-channelized).

The data collection effort consisted of videotaping right-turn operations at each of the two sites for more than 6 hours. At the Street Road/Southampton Estates location, operations were taped from 9:00 a.m. until 4:00 p.m.; while at the York Road/County Line location, the hours observed were from 8:30 a.m. until 2:30 p.m.

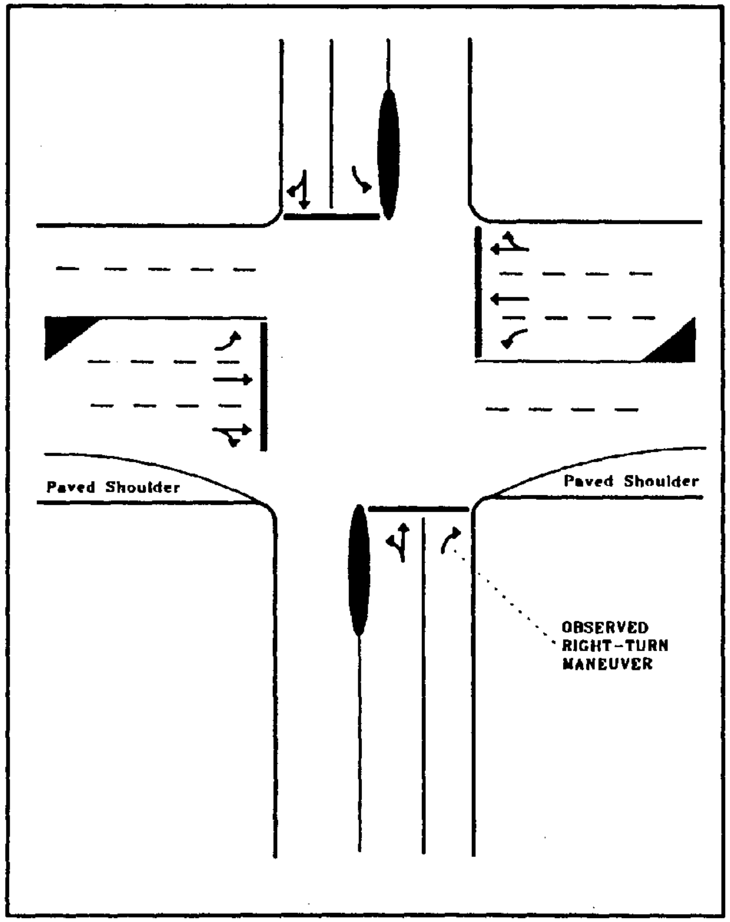


Figure 24. Street Road/Southampton Estates intersection without channelized right-turn lane.

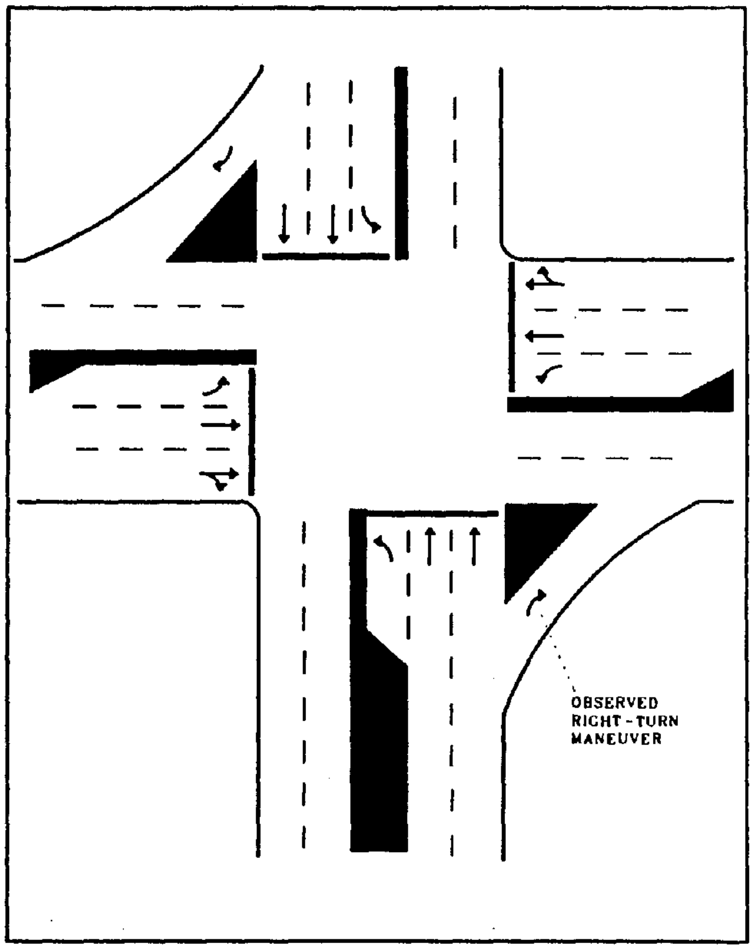


Figure 25. York Road/County Line Road intersection with channelized right-turn lane.

The video system consisted of three cameras, a quad splitter, a time-date generator, a videocassette recorder, two monitors, a microphone system, and other miscellaneous equipment powered from a portable generator. All cameras were mounted on a pole attached to the data collection van and they provided an adequate view of the intersection and the approaches of interest. The first camera was focused on the driver performing the right-turn maneuver and was a close-up shot acquired with a zoom lens. This camera was controlled from within the van with a pan-and-tilt control and a zoom control. The second camera was focused on the entire intersection and allowed for the determination of when a driver began the right-turn maneuver, the path taken in making the maneuver, and the gap accepted. The third camera was focused downstream of the intersection and allowed for the determination of when a driver had completed the intersection maneuver and had accelerated to a reference point located 36.6 m (120 ft) downstream of the intersection. In the fourth quad on the videotape were a clock and stopwatch produced with the time-date generator that ran throughout the data collection period.

In addition to the video data, manual observations of license plate numbers were recorded for those drivers of interest. The vehicles that were of interest for this study were those passenger cars that were free-flowing, i.e., traveling far enough behind another vehicle such that they were not influenced by that vehicle. Pickups, vans, minivans, and utility vehicles were not included in the sample due to differences in driver eye height. As in the left-turn study, license plate numbers were sent to the Bureau of Licensing in Harrisburg, Pennsylvania for information on the age and gender of the vehicle owner in order to confirm the age and gender observations made in the field. The results of this confirmation task resulted in 48 older drivers at the Street Road/Southampton Estates location and 33 older drivers at the York Road/County Line location. Sample sizes of 42 and 50 younger drivers were obtained for the Street Road/Southampton Estates and York Road/County Line locations, respectively.

Measures recorded from the videotape for each subject driver included: (1) the "wait time" between the moment a driver arrived at the intersection and the moment the right-turn maneuver was begun; (2) the number of vehicles in queue behind the right-turning vehicle at the time the right-turn maneuver was made; and (3) the trajectory of the turning path, coded from *0* to *2* as follows: *0* = driver making the right-turn maneuver encroached onto the right shoulder as the turn was made; *1* = driver properly turned into the right (curb) lane; and *2* = driver turned into the center (median) lane.

All data were entered into a database and the MOE's of interest were produced for each age group and for each right-turn scenario. Data analyses were performed using an analysis of variance (ANOVA) for comparing the continuous MOE's (e.g., time), while a Fishers Exact Test was used for comparing the frequency data (e.g., number of turning paths). A 95 percent confidence level was selected for determination of significant differences in the statistical tests.

Results. As with the left-turn maneuver, there were very few differences between driver age groups for the two right-turn geometric designs evaluated. Neither the gaps accepted when turning right on red nor the turning path taken was significantly different at either location. However, the maneuver time, or time taken to reach a reference point 36.6 m (120 ft) downstream of the intersection, was significantly greater for older drivers compared to younger drivers at the non-channelized location. This result suggests that the channelized right-turn lane may provide for better acceleration for older drivers when compared to the non-channelized location.

OLDER ROAD USERS EXPERT PANEL MEETING

Objectives and Proceedings

A nine-member panel made up of five traffic/highway engineers, three applied experimental psychologists, and one gerontologist was convened for a 1-day meeting, following the conduct of the preliminary laboratory and field studies. This meeting was hosted by four project team members and was also attended by three SAIC personnel representing FHWA. A list of participants is presented in Table 10. The objective in this meeting was to discuss the implications of the Preliminary Problem Identification Studies conducted as described above, allowing each panel member to apply his/her expertise to the present research issues and preliminary project findings in an effort to specify and prioritize design-related problems for older drivers and pedestrians at intersections.

Table 10. Older road user expert panel participants.

Panelists	Engineers	Miguel Gavino	Washington State DOT
		Donald Gilbertson	Wisconsin State DOT
		Richard Skopik	Texas State DOT
		Mark Freedman	Westat
		Tim Neuman	CH2M Hill
	Psychologists	Karlene Ball	Western Kentucky University
		Neil Lerner	COMSIS Corp.
		A. James McKnight	National Public Services Research Institute
	Gerontologist	Germaine Odenheimer	Harvard Medical School
Project Team	Engineers	David Harkey	UNC - Hwy. Safety Research Center
		Stanley Byington	Consultant, Transportation Engineering
	Psychologists	Loren Staplin	The Scientex Corporation
		Kathy Lococo	The Scientex Corporation
FHWA Representatives		Robert Peters	SAIC
		Essie Kloeppel	SAIC
		John Farbry	SAIC

The panel proceedings were characterized by a diversity of perspectives and, for certain topics, a consensus of opinion that guided development in later project tasks of geometric and operational enhancements to accommodate older road users. In particular, results of the panel discussion provided guidance regarding the most important operational scenarios and geometric elements to incorporate into later laboratory and field studies, while also identifying independent variables, measures of effectiveness, and other aspects of research methodology to maximize the validity and generalizability of this work.

Most prominent of the suggestions by engineers and psychologists alike was to study a few things well instead of trying to study too much and obtaining confounded data. The panel suggested limiting field studies to left turns, and varying parameters such as the offset angle/sight distance for turning drivers, and/or the intersection width (the throat on the receiving leg), and/or the operating speed of the facility. In addition, it was suggested that it would be most useful to limit observations to drivers turning left at signalized intersections during the permissive phase, when they are turning from the major street to the minor street (or to another major street), because this seems to be the most problematic scenario. One particular configuration singled out for study was positive offset left-turn lanes. This is because a positive offset brings the conflict vehicle in view of the turning driver, and it moves the turning driver closer to his/her destination, which should reduce maneuver time.

A summary of the principal conclusions emerging from the panel discussion follows.

Conclusions

(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 of further study in this project, were not identified as a priority during the panel discussion.

(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**. In addition, specific warrants may be required to govern the application of enhancements developed in this project, if pedestrian volumes are high and/or the accident history at a given location indicates exaggerated difficulties for pedestrians.

(3) Guidelines for conduct of the following laboratory study in this project were to examine: (a) positive (versus aligned versus negative) offset geometries for left-turn lanes; and/or (b) varying throat width on the receiving leg of intersections; and/or (c) varying lane width (2.7 m [9 ft] vs. 3.7 m [12 ft]) on the intersection approach leg. Further guidance provided by the panel emphasized the need to:

- Select MOE's that 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).
- Include a range of realistic conflict scenarios in intersection test stimuli presented in the laboratory (i.e., do not study alternative geometries "in isolation," without traffic and pedestrians in the scene).
- Include, as an experimental control, the consistent use of baseline traffic control devices (TCD) and delineation/marking treatments across test conditions as defined in the FHWA "Traffic Operations Control for Older Drivers" study.

(4) Guidelines for conduct of the following field study in this project were to 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 receiving leg. Also, the panel indicated a need to:

- Consider "margin of safety," critical gaps, and traffic conflicts as MOE's.
- Employ enough test sites within each geometric condition, when studying alternative designs, to overcome the "noise" in driver performance introduced by confounding factors such as operational and traffic control differences (which inevitably will vary even within matched sites).
- Collect data during actual operations with test drivers, as opposed to data collection on a closed course, to maximize the validity and generalizability of study findings.
- 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).
- Strive for a consistent operating speed across data collection sites as an experimental control (also noting that higher speed locations are more critical).
- Provide for a consistency of extraneous (i.e., non-manipulated) geometric elements (e.g., curb radius, shoulder width) as an experimental control.

LABORATORY AND FIELD INVESTIGATIONS

OVERVIEW AND OBJECTIVES

The major empirical studies performed in this research contract are described in this section. It may be recalled that prior tasks identified certain geometric elements as having the greatest impact on the safety and ease of use of intersections by older road users, namely:

- Degree of offset of opposite left-turn lanes.
- Degree of skewness of a leg joining an intersecting roadway at an angle other than 90°.
- Radius of corner curb cuts at intersections without right-turn channelization.
- Geometry (curvature) of turning path, including acceleration-lane characteristics, where right-turn channelization is present.
- Location (distance downstream) of the lane drop when a pavement-width reduction occurs for through lanes across an intersection.

Of these priorities, it was determined that the most appropriate focus of the laboratory studies in this effort was on: (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 primary objectives of this work are summarized below.

Laboratory Studies

Two experiments were conducted in the laboratory to answer questions about intersection design as a function of user type (drivers versus pedestrians). The first experiment was a study of 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 second experiment was a study of pedestrian crossing decisions by individuals standing at a curb at a crosswalk, which focused on their perceptions of safety and willingness to cross at different times during the WALK and flashing DON'T WALK pedestrian control signal indications. The purpose was to examine the implications for mobility for older and younger pedestrians as a function of varying median refuge island configurations as permitted by the alternative geometries examined in the first experiment.

Field Studies

Two controlled field studies were conducted to study the effects of left-turn lane and right-turn lane geometry, and right-turn curb radius on the performance of drivers as a function of age and gender. In the study of the geometry of left-turn lanes, the objective was to examine the effects of varying degrees of offset on the performance of left-turning drivers. In the study of the effects of right-turn lanes and right-turn curb radii, the purpose was to evaluate the effects of channelization, acceleration lanes, degree of skew at which the lane met the mainline, and the effect of curb radii on the performance of drivers executing right turns. Also, an observational field study of pedestrian crossing behavior was conducted to measure signal violation rate, and interviews were conducted to obtain subjective measures of ease of intersection use and the desirability of median refuge islands by different age-gender groups at locations with and without pedestrian refuge islands.

The following description of these studies is organized according to the geometric element of interest and the type of intersection user (driver vs. pedestrian). The independent and dependent variables, test samples, methodology, and results are described first for the laboratory study of alternative left-turn lane geometry, followed by the field study that also measured driver performance as a function of left-turn lane geometry. Next, the laboratory and field studies conducted to measure pedestrian preferences for alternative median/refuge island configurations are reported. Finally, this section concludes with a discussion of the field studies conducted to evaluate driver performance as a function of right-turn lane geometry.

ALTERNATIVE LEFT-TURN LANE GEOMETRY

Laboratory Study

Independent Variables. The geometric element varied in this controlled, laboratory study was the degree of offset for opposite left-turn lanes. This variable refers to the distance from the inner edge of a driver's (experimental subject's) left-turn lane to the outer edge of the opposite left-turn 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., reduced sight distance). The level of blockage depends on how the opposite left-turn lanes are aligned with respect to each other. 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, the size of the effect of a given change in sight distance on gap judgments is unknown. Also, increasingly positive offset geometries result in longer crossing distances for pedestrians.

As diagrammed in Figure 26, 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).
(d) 1.8-m (6-ft) "partial negative" offset.

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 mi/h, 45 mi/h, and 55 mi/h]); (3) oncoming traffic density, i.e., the spacing between successive vehicles in the opposing through-traffic stream (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 (passenger car or semi-tractor trailer).

Dependent Variables/Measures of Effectiveness. The measures of effectiveness for the laboratory study of opposite left-turn lane geometry 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.*[1] 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 turn 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."

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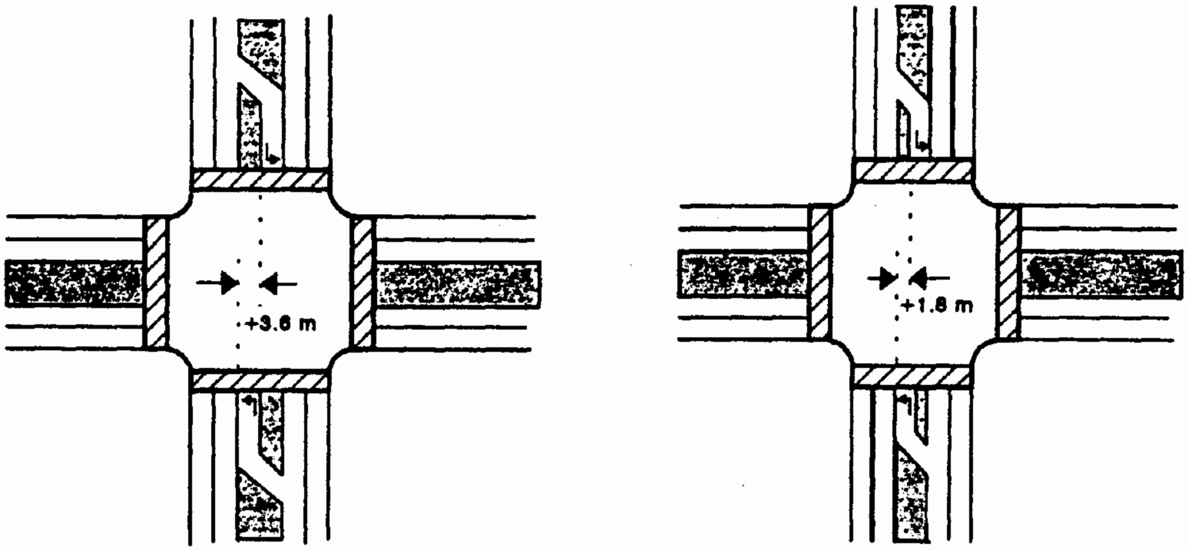
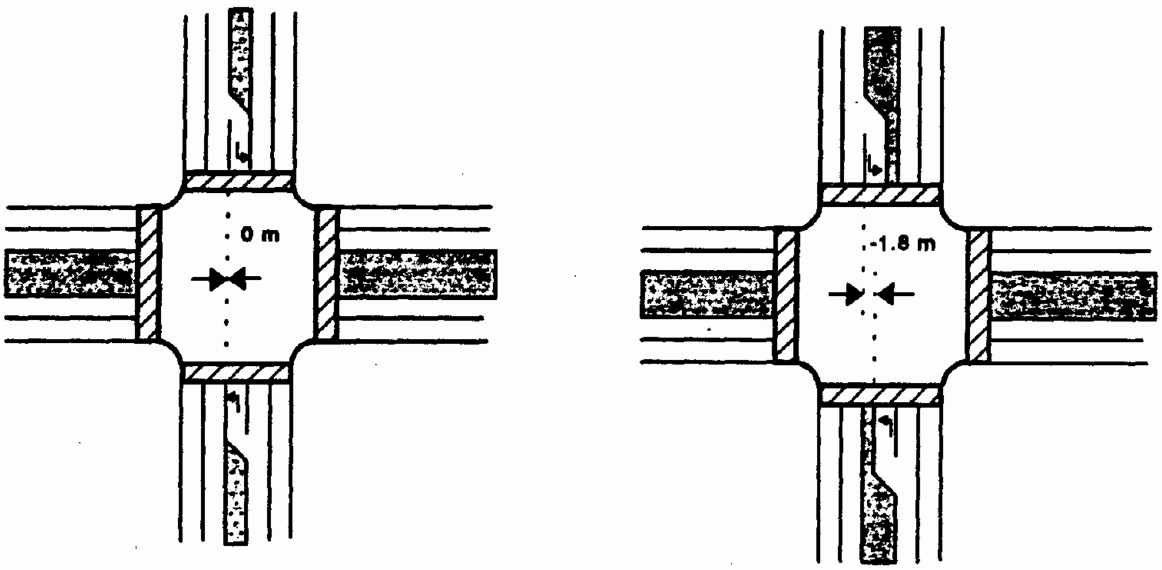
[1] Because all responses were sorted into only two classifications—safe gap versus unsafe gap—depending upon their relationship to the threshold distance for this measure, the complement of "unsafe gaps accepted" would be "safe gaps rejected." The frequency of this outcome for each study condition was not separately analyzed, however, since an identical pattern of differences (in the opposite direction) would result.



(a) full positive offset (b) partial positive offset



(c) aligned (d) partial negative offset

Figure 26. Alternative intersection geometries examined in the laboratory.

Test Sample. The test sample for this research is described by their demographic characteristics, visual performance capability, and individual responses to questions concerning their exposure as drivers and pedestrians.

The test sample consisted of 24 licensed drivers in each of 3 age groups—*25-45; 65-74*; and *75+*—for a total sample of 72 subjects. In the interest of obtaining a representative distribution of driver capabilities, a quasi-random sample of test subjects was recruited through solicitations at Pennsylvania photo license centers, where a person's birth date (month of year) is the determining factor as to who appears on any given day. Additionally, individuals from the subject pool established in the earlier Problem Identification Studies were invited to participate. A total of $60 was offered for completion of both experiments in the laboratory study. Sample demographics are displayed in Table 11.

Table 11. Sample characteristics for the opposite left-turn lane geometry laboratory study.

Driver Age	Number of Subjects	Number (%) of Males	Number (%) of Females	Mean Age	Median Age
25-45	24	12 (50)	12 (50)	34.4	35
65-74	24	12 (50)	12 (50)	68	67
75+	24	14 (58)	10 (42)	78.6	77

Measures of visual capability were determined for all prospective study participants; these included assessments of static acuity and contrast sensitivity. The acuity measure was based on binocular or "best eye" performance on a Snellen wall chart under photopic luminance conditions without glare. Subjects were instructed to wear glasses if required for driving. Initially, a criterion for study participation of 20/40 (corrected) vision was planned, reflecting the licensing requirement in the majority of states. However, two individuals age 75+ and one individual between the ages of 65 and 74 with acuity measured at 20/60 were accepted as subjects. While this was done in part for practical reasons—to fill the desired sample sizes—a wish to avoid bias toward the "superfit" members of the older cohorts also suggested that this strategy would most likely yield a sample more representative of the actual driving population. The remainder of subjects in all age groups demonstrated 20/40 or better visual acuity.

Because spatial vision declines with age, especially over age 40, and loss of contrast sensitivity will reduce drivers' ability to detect the diffuse edges defining lane and pavement boundaries, curb lines, and raised median barriers, contrast sensitivity thresholds were obtained for sine-wave gratings with spatial frequencies of 1.5, 3, 6, 12, and 18 cycles per degree (cpd). A Vistech VCTS 6500 wall chart was used to collect these measures. Each row on this chart pertains to one of the five spatial frequencies, and contains nine circular test patches, where the first patch displays high-contrast sine-wave gratings and each successive patch displays a lower contrast than the one before it. The last patch in each sequence is solid gray and contains no gratings. The test patches show bars that are slanted in one of three orientations: straight up and down, tilted to the left, or tilted to the right. The be-st threshold is obtained when a test subject can identify bars of the lowest contrast in the last several patches of each spatial frequency.

Each subject's responses were scored—first, as either within a "normal range" or "below normal," according to criteria for 90 percent of the population without known pathology, between the ages of 10 and 70, as published by the test chart designers. The percentage of subjects in each age group scoring in the *below-normal range* is presented in Table 12.

Table 12. Percentages of each age group in below-normal range (Ginsburg, Evans, Cannon, and Mulvanny, 1984) for contrast sensitivity measures at spatial frequencies.

Driver Age Group	Spatial Frequency				
	CS-1.5	CS-3	CS-6	CS-12	CS-18
25-45	0	0	0	0	0
65-74	0	8	37	21	13
75+	4	21	50	17	33

Next, contrast thresholds were calculated from the contrast sensitivity scores obtained using the Vistech VCTS 6500 chart, and are presented in Table 13. Contrast sensitivity is the reciprocal of the threshold contrast needed to just detect a target. In this test, the contrast of the test patches ranges from zero contrast to contrast above and below visual threshold in approximately 0.1 log unit steps. Therefore, the lower the calculated contrast threshold value, the better the contrast sensitivity. One subject in the age 75+ group could not discern the orientation of the bars in the first test patch for the 12-cycle/degree test; and two subjects in the middle age group (65-74) and three subjects in the oldest age group (75+) could not correctly identify the orientation of any of the 18-cycle/degree test gratings. These subjects were thus excluded from the calculations of mean threshold values for these spatial frequencies, rather than arbitrarily assigning dummy values; thus, the calculated thresholds reported in these cells in Table 13 are marginally lower (i.e., better) than if threshold measures for these isolated subjects, whose performance was "off the chart," had been obtained.

Table 13. Mean contrast threshold value for each age group in study sample as a function of spatial frequency.

Driver Age Group	Spatial Frequency				
	CS-1.5	CS-3	CS-6	CS-12	CS-18
25-45	0.012	0.010	0.009	0.023	0.058
65-74	0.020	0.019	0.013	0.056	0.100
75+	0.023	0.021	0.017	0.062	0.133

Finally, participants were asked to provide the following information to determine their intersection exposure as drivers and pedestrians, and to provide indications of their difficulties in negotiating these sites: (1) the approximate number of miles driven each week; (2) how often they used pedestrian crosswalks; (3) their level of avoidance of left turns; and (4) their involvement in left-turn accidents, if any. Table 14 reports participants' responses to these questions.

Table 14. Self-reports of exposure as drivers and pedestrians, avoidance of left turns at intersections, and involvement in left-turn accidents by participants in the laboratory studies.

Driver Age	Miles Per Week		Intersection Use as Pedestrian (%)			Avoid Left Turns at Intersections (%)			Involved in Accident (%)
	Mean	Median	Never	Sometimes	Often	Never	Sometimes	Often	
25-45	256	212	21	58	21	87	13	0	8
65-74	135	100	37	50	13	54	21	25	21
75+	86	75	38	58	4	37	0	63	16

1 mi = 1.61 km

Methodology. A specialized, video-based driving simulator was used for presenting dynamic and static intersection test stimuli, which provided scenes that ensured the correct perspective and motion-in-depth cues. This was an essential component of the data collection plan, in that the accuracy of angular motion cues during simulation is crucial to gap judgments and related perceptual measures. This stimulus attribute was ensured through the proper relationship of projected image size and viewing distance by the subject for the field of view captured at the time of stimulus preparation. The laboratory driving simulator is diagrammed in Figure 27.

The stimulus scenes were prepared using a 1/24-scale "terrain board" model of an intersection, also including approximately 300 m (984 ft) of roadway leading to the intersection, plus the areas along the sides of the roadway. These roadway features were video recorded from the perspective of a driver waiting across the intersection (at the end of the left-turn storage lane) to turn left. An overall field of view of approximately 45° was captured, providing a "far corner-to-far corner" view of the opposite side of the intersection. This field of view was split between two cameras for filming and two video projection systems for playback, such that the two images overlapped to create a seamless 45° view. The traffic control devices in this view included overhead signals for the through lanes on the subject's side of the roadway, displaying steady green balls, plus a left-turn signal directly across from the subject that also displayed a steady green ball (signifying a permissive phase of operation).

The projection modules used for displaying the intersection test stimuli on each trial consisted of cathode ray tube (CRT) projectors, first-surface glass mirrors, and neutral gray rear-projection screens. A Hi8mm recording format was used for filming, and laser discs provided the storage/playback medium. Additional components of the experimental apparatus included

1–1988 Dodge Dakota cab (engine removed) with factory steering wheel/column, brake and accelerator pedals, dashboard instruments, inside rearview mirror, and front windshield (rear window removed); mounted on fixed platform with coil-spring suspension and high-frequency vibration generator

2–high-resolution video projection module, including: (2a) Ampro 3000D CRT data projector; (2b) first surface glass mirror; (2c) acrylic rear-projection screen (neutral tint), 149 x 198 cm

3–step-up platform to simulator cab

4–experimenter's control station

5–I/O box containing relay and A/D control cards to link simulator instrumentation to executive PC

6–486 DX/66 executive PC/monitor

7–laser videodisc players (2), Pioneer LD-V8000

8–OLTLG stimulus projection module monitor, Panasonic CT2583

9–data printer, Epson LQ-1070+

10–LED response feedback display

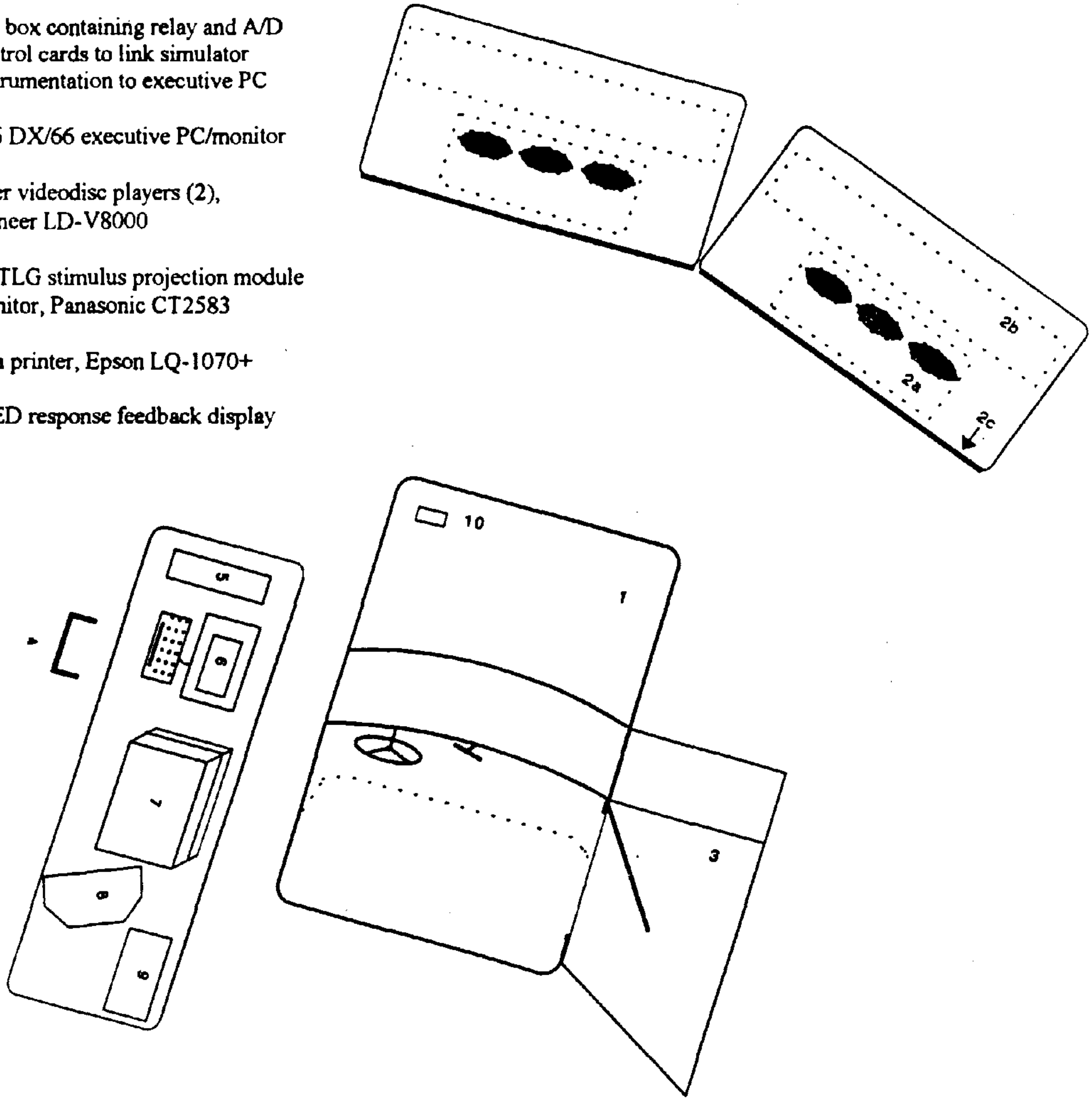


Figure 27. Driving simulator used in laboratory data collection.

two laser disc players. Two players were used since the field of view was divided into two adjacent sections, as noted above, for improved image quality. The laser disc players had variable speed-control capability; this feature allowed filming at a single speed, with later playback of the opposing traffic stream at different speeds as required by the present research design.

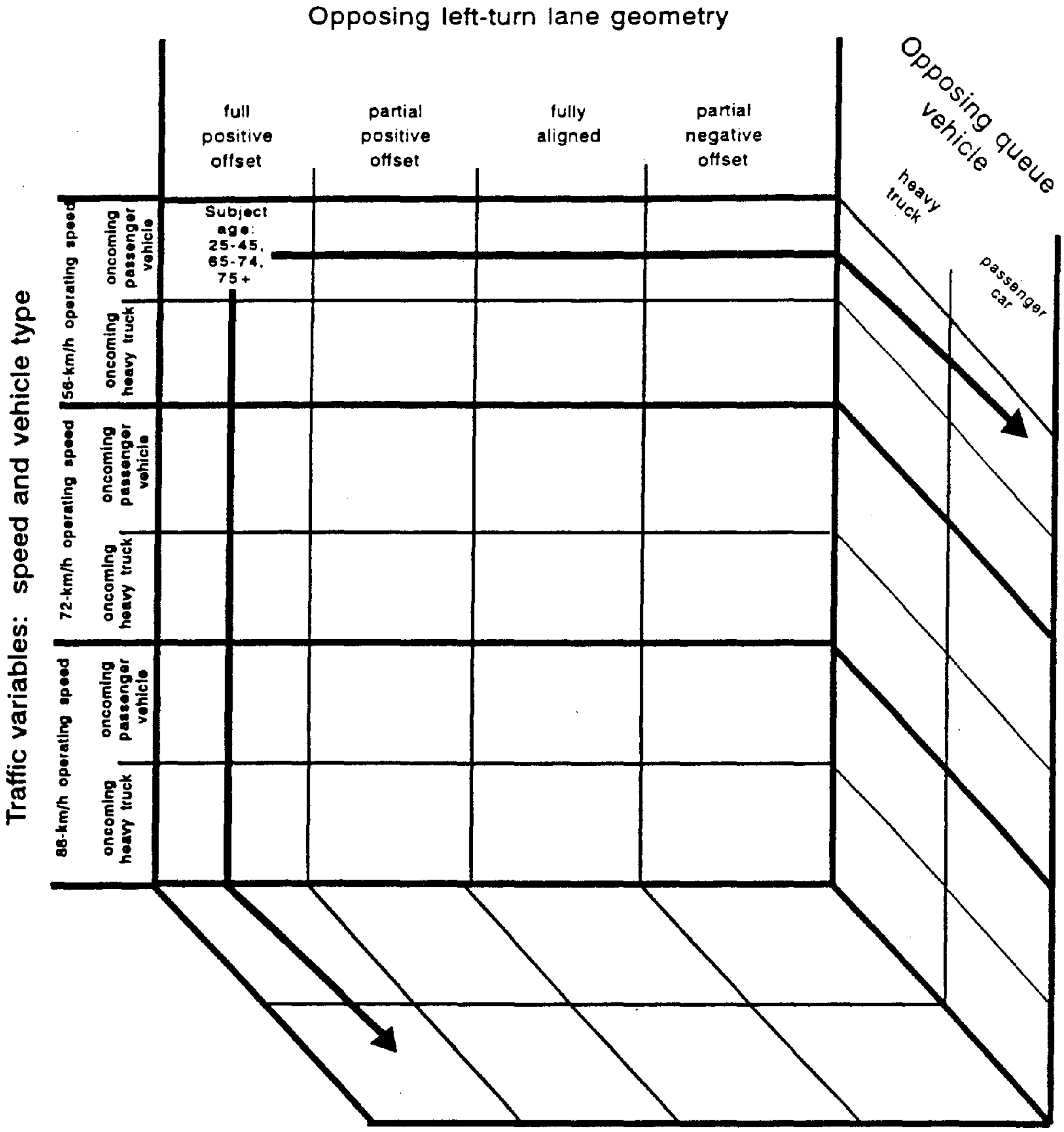
As subjects sat in the simulator cab, which was "positioned" at the stop bar in the left-turn bay, they watched a stream of vehicles approaching in one of the opposing through lanes and they made "go/no go" turn decisions using a gaming device trigger apparatus. Squeezing the trigger meant that they **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. A green light-emitting diode (LED) on the hood of the simulator provided feedback that they were responding with a "go" decision; a red LED provided visual feedback that they were making a "no go" response.

The laboratory driving study employed a repeated-measure research design, in which all subjects generated responses for all dependent measures under all test conditions. The test conditions, in turn, were defined by combinations of the independent variables and blocking variable identified earlier. A total of 24 trials were performed for each level of the blocking variable described by the type of vehicle waiting in the opposite left-turn storage lane, i.e., a passenger car or a heavy truck. These 24 trials represented 4 levels of opposite left-turn lane geometry (OLTLG), where, in each case, subjects were presented with 2 types of oncoming vehicles, each traveling at 3 different speeds. The resulting test conditions for the laboratory study of driver response are diagrammed in the matrix shown in Figure 28.

In addition, one baseline condition was performed for each intersection geometry where subjects made gap acceptance judgments (using the trigger device) for an oncoming passenger car and an oncoming heavy truck, at each of the three speeds tested, but without any vehicles blocking their view in the opposite left-turn lane. Instead of performing responses for a continuous stream of vehicles presenting nine different gaps randomly varied within the sequence—as was the case for all test conditions shown in Figure 28—the baseline data were obtained only for a single vehicle approach.

Results. The results of the laboratory study are summarized by tables of descriptive statistics for critical gap size and perceived hazard ratings, and for the frequency of unsafe gap acceptance/safe gap rejection events, for all test trials (i.e., other than control conditions). For the responses obtained under control (baseline) conditions where no other vehicle was present in the opposite turn lane, results indicating the judged "last safe moment" to turn ahead of the oncoming vehicle are summarized in this section. The outcomes of inferential statistical tests documenting the significance of observed differences (main effects and interactions) for quantitative variables, and the results of non-parametric tests of differences in event frequencies, are also reported. Supporting graphs and figures are provided to illustrate selected findings that are statistically and/or operationally significant.

An overall effect of geometry on critical gap size was observed, such that the full positive condition resulted in a critical gap 30 to 40 m (98 to 130 ft) shorter than the other geometries



Traffic density: Alternative spacings between vehicles will result in gap acceptance measures for nine randomly distributed gaps varying between 30.5 and 274.4 m, in 30.5-m increments, for each cell in the test conditions matrix.

NOTE: All subjects provided responses for all cells in this test conditions matrix.

Figure 28. Test conditions matrix for the laboratory study of alternative left-turn lane geometry.

tested. Increases in gap size were shown with increases in driver age, regardless of opposite left-turn lane vehicle type, with the age 75+ group requiring the largest gaps. The full positive geometry resulted in the shortest gaps compared to the other three geometries, and the partial negative offset resulted in the longest critical gap sizes. Critical gap sizes for the partial positive and aligned geometries were nearly identical. The effect of geometry alone is most clearly illustrated by the critical gap functions displayed in Figure 29; in this figure, the critical gap size for each geometry may be read on the abscissa as the value that corresponds to the 50 percent value on the ordinate for each curve.

Table 15 presents the critical gap size (in seconds) as a function of geometry and driver age, with a passenger car in the opposite storage bay; and the data summarized in Table 16 show the results when a heavy truck was the blocking vehicle. The data in these two tables are collapsed across oncoming vehicle type. In both cases, an increase in critical gap size with increasing age is typical, with the greatest increase observed for the age 75+ group. Also evident was the contrast between the shorter gaps for the full positive condition versus the other three geometries. At the same time, the partial negative offset condition consistently resulted in the longest critical gap sizes.

Table 15. Critical gap size (in seconds) as a function of intersection geometry and driver age, with a passenger car in the opposite turn bay.

Driver Age Group	Intersection Geometry			
	Full Positive	Partial Positive	Aligned	Partial Negative
25-45	5.7	6.3	6.5	6.6
65-74	5.6	6.8	7.1	7.5
75+	6.9	8.8	8.8	9.2

Table 16. Critical gap size (in seconds) as a function of intersection geometry and driver age, with a semi-tractor trailer in the opposite turn bay.

Driver Age Group	Intersection Geometry			
	Full Positive	Partial Positive	Aligned	Partial Negative
25-45	4.5	6.4	6.3	6.6
65-74	5.1	6.7	6.5	7.2
75+	5.7	8.9	8.2	9.2

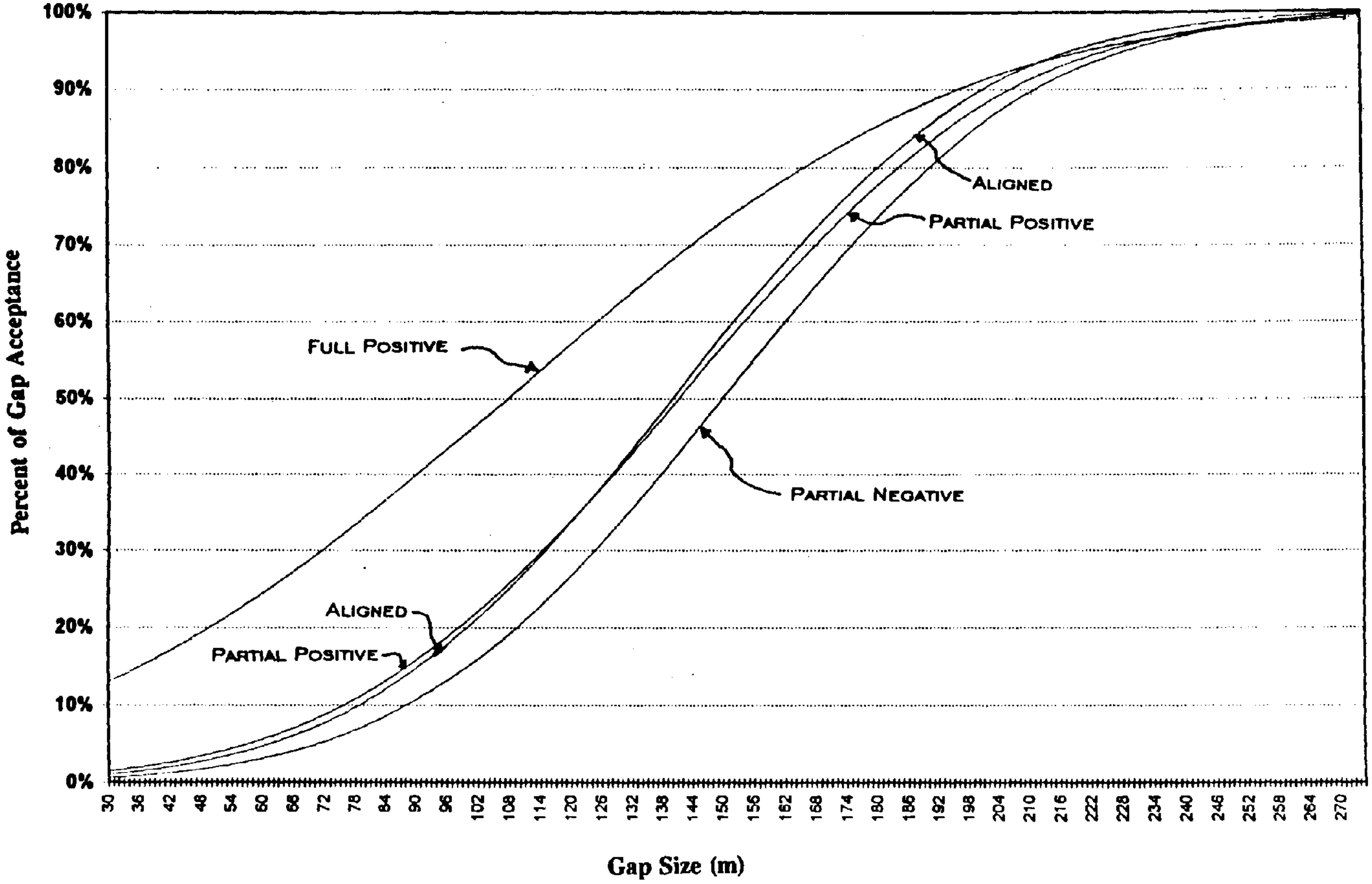


Figure 29. Continuous PROBIT functions relating gap size (in meters) to gap acceptance responses, for each intersection geometry tested in the laboratory study.

Next, the influence of oncoming vehicle type (passenger car versus heavy truck) is revealed by the data summarized in Tables 17 and 18. As shown, drivers in all age groups tested required larger gaps when a heavy truck was approaching, versus a passenger car, under all combinations of the other variables represented in these tables. Again, a trend showing an increase in critical gap size with increasing driver age was common, especially for the oldest (75+) group; and the full positive offset geometry again produced the shortest gaps. However, age differences were minimized with the full positive geometry—even resulting in slightly shorter critical gap sizes for the 65- to 74-year-old group than for drivers ages 25-45 for both types of blocking vehicles.

Table 17. Critical gap size (in seconds) as a function of intersection geometry, driver age, and oncoming vehicle type, with a passenger car in the opposite turn bay.

Driver Age Group	Intersection Geometry							
	Full Positive		Partial Positive		Aligned		Partial Negative	
	Car	Truck	Car	Truck	Car	Truck	Car	Truck
25-45	4.8	6.6	5.7	6.8	6.1	6.8	6.5	6.8
65-74	4.4	6.8	6.2	7.3	6.7	7.4	6.9	8.1
75+	5.2	8.6	7.8	9.6	8.3	9.2	8.2	10.2

Table 18. Critical gap size (in seconds) as a function of intersection geometry, driver age, and oncoming vehicle type, with a semi-tractor trailer in the opposite turn bay.

Driver Age Group	Intersection Geometry							
	Full Positive		Partial Positive		Aligned		Partial Negative	
	Car	Truck	Car	Truck	Car	Truck	Car	Truck
25-45	4.3	4.7	5.9	6.6	6.0	6.6	6.2	7.0
65-74	4.2	6.0	6.3	7.2	6.3	6.7	6.8	7.7
75+	5.1	6.2	8.4	9.4	8.0	8.4	8.9	9.5

Figures 30 and 31 present the critical gap sizes (in seconds) as a function of driver age, geometry, and oncoming vehicle type (across oncoming vehicle speed), for conditions when the blocking vehicle in the opposite left-turn lane was a passenger car (Figure 30) and a semi-tractor trailer (Figure 31).

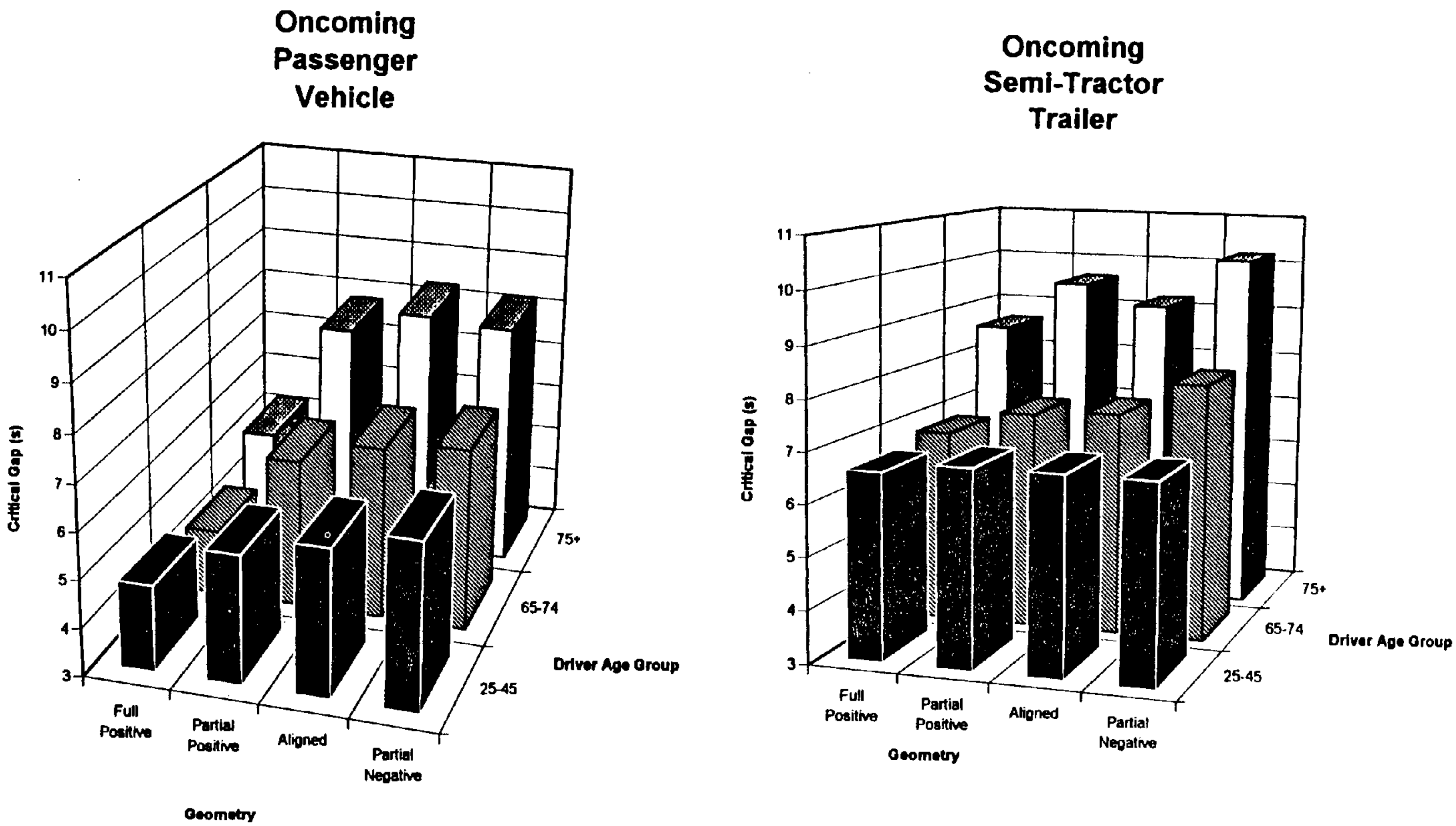


Figure 30. Laboratory study critical gap size (in seconds) as a function of intersection geometry, driver age, and oncoming vehicle type, with a passenger car in the opposite turn lane.

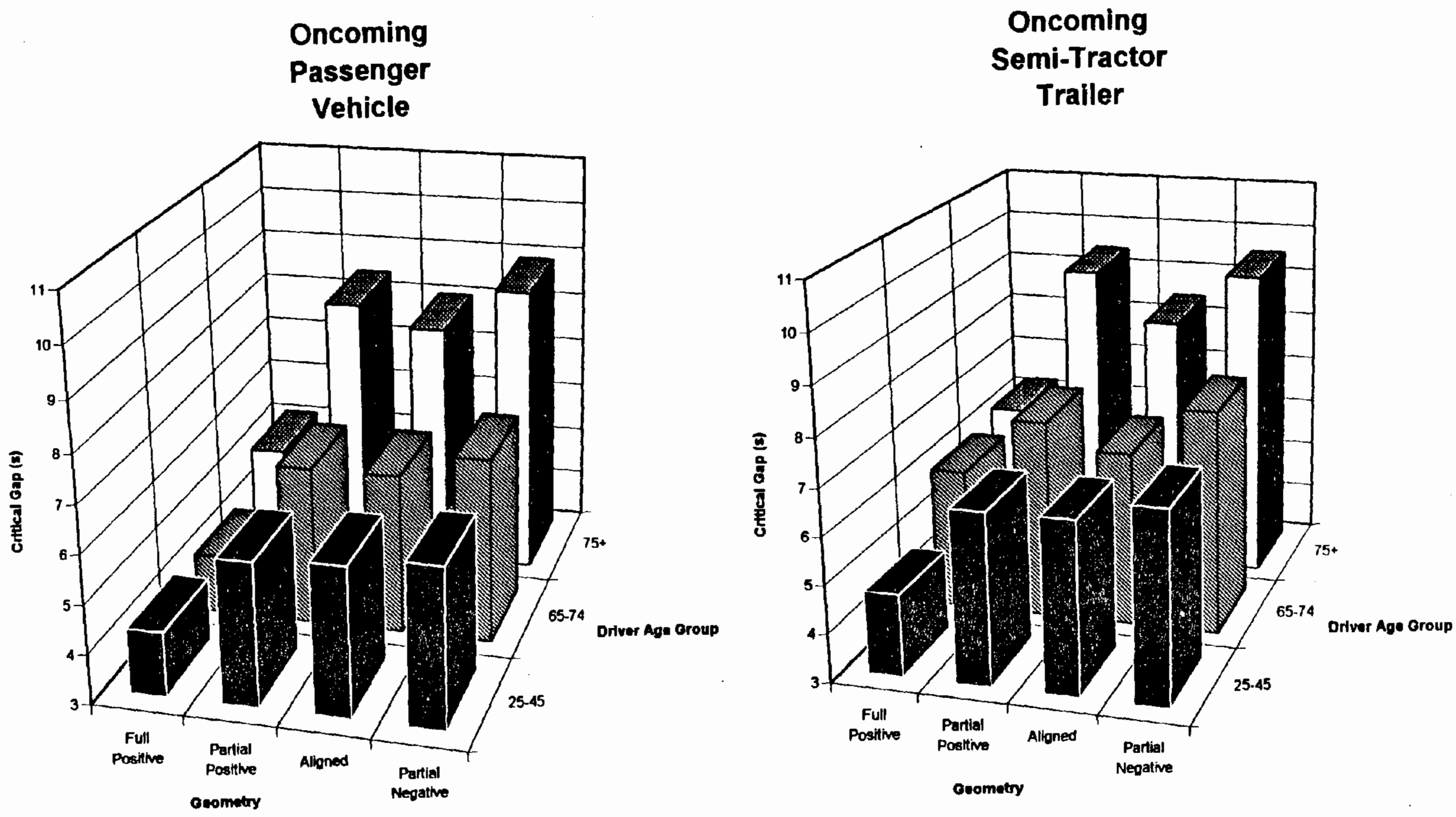


Figure 31. Laboratory study critical gap size (in seconds) as a function of intersection geometry, driver age, and oncoming vehicle type, with a semi-tractor trailer in the opposite turn lane.

Finally, oncoming vehicle speed is taken into account in the results presented in Tables 19 and 20. While critical gap size is typically shorter with the full positive geometry and longer for older drivers, and while oncoming trucks resulted in larger gap requirements than oncoming cars, as a rule, an increase in the speed of the oncoming vehicle did **not** produce larger critical gap sizes. The possibility exists that this outcome reflects limitations in the video stimulus display methodology used in the laboratory study, i.e., display resolution was not sufficient to provide the identical angular size change information for the target vehicle—a critical cue for perception of closing velocity—afforded by a driver's view of oncoming traffic under actual operating conditions.

The clearest pattern of differences for the critical gap measure was observed at the level where data are sorted by intersection geometry, driver age, and oncoming vehicle type, collapsed across oncoming vehicle speed (i.e., a decrease in critical gap size for the full positive offset geometry, and an increase in this measure as driver age increases and when an oncoming vehicle is a heavy truck [versus a passenger car]). Since the PROC PROBIT analyses were performed at the group level, however, no measures of within-subjects variance are available for this derived dependent variable, and analysis of variance at the level of individual subject observations are not permitted. An ANOVA at the level of group data is also problematic, since the single data point for a given group under a given test condition violates sample size assumptions for this procedure.

The data for the control conditions are reported next, reflecting the distance of the oncoming vehicle, during a single approach from the farthest (scaled) separation (274.4 m [900 ft]), when each subject indicated that it would no longer be safe to proceed with a left turn. As a reminder, this measure of the "last safe moment" to turn was obtained when there was no vehicle in the opposite left-turn lane to block the subjects' view across the intersection. The direct, quantitative measures of the least safe gap size were analyzed using both descriptive and inferential (ANOVA) statistical procedures.

The results summarized in Table 21 indicate two clear findings: (1) the judged least safe gap size increases consistently with increasing driver age, with the largest change occurring between the 65-74 and the 75+ age groups; and (2) the least safe gap size is virtually unchanged across geometry within a given driver age group, **except** for a sharp decrease in this measure for the partial negative offset condition, relative to the other three geometries tested. A similar pattern is also evident in Table 22, where a finer examination of these data reveals the influence of oncoming vehicle type. Here it is not only apparent that the minimum gap size required by drivers turning left at an intersection is typically larger when a heavy truck is approaching than when a passenger car is approaching, but the trends in these data described above can also be discerned—i.e., increasing gaps with increasing driver age, and notably smaller gaps under the (partial negative) geometry, which affords the poorest visibility of oncoming traffic.

The mean least safe gap size (in meters) for each age group, left-turn lane geometric configuration, and oncoming vehicle type is presented in Figure 32, across oncoming vehicle speed.

Table 19. Critical gap size (in seconds) as a function of intersection geometry, driver age, oncoming vehicle type, and speed (km/h), with a passenger car in the opposite turn bay.

Driver Age	Intersection Geometry																							
	Full Positive						Partial Positive						Aligned						Partial Negative					
	Car			Truck			Car			Truck			Car			Truck			Car			Truck		
	56	72	88	56	72	88	56	72	88	56	72	88	56	72	88	56	72	88	56	72	88	56	72	88
25-45	6.4	4.4	3.5	8.6	5.8	5.4	7.2	5.4	4.5	8.4	6.4	5.6	7.8	5.7	4.9	8.5	6.2	5.7	8.1	6.3	5.0	8.2	6.3	5.9
65-74	5.7	4.2	3.4	8.6	6.6	5.3	7.7	6.0	5.0	8.9	7.0	6.1	8.5	6.3	5.3	9.2	7.2	5.9	8.5	6.6	5.6	9.9	7.8	6.5
75+	5.8	5.2	4.5	9.9	8.5	7.4	9.3	8.1	6.1	11.8	9.8	7.9	9.9	8.4	6.5	11.1	9.2	7.4	10.0	8.2	6.4	12.5	9.9	8.1

Table 20. Critical gap size (in seconds) as a function of intersection geometry, driver age, oncoming vehicle type, and speed (km/h), with a semi-tractor trailer in the opposite turn bay.

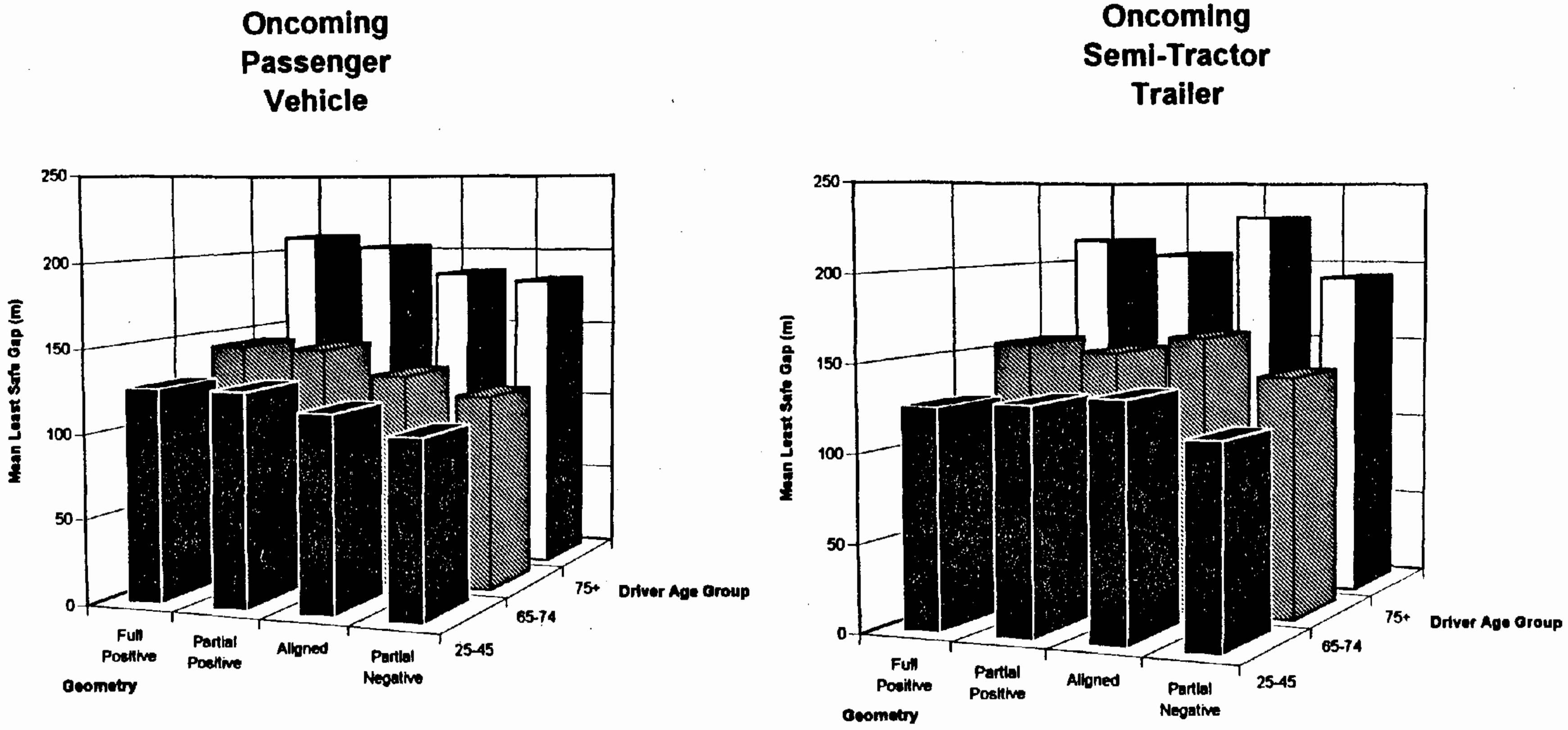
Driver Age	Intersection Geometry																							
	Full Positive						Partial Positive						Aligned						Partial Negative					
	Car			Truck			Car			Truck			Car			Truck			Car			Truck		
	56	72	88	56	72	88	56	72	88	56	72	88	56	72	88	56	72	88	56	72	88	56	72	88
25-45	5.5	4.0	3.3	5.5	4.0	4.7	7.5	5.5	4.8	8.9	6.2	5.2	7.5	5.7	4.9	7.9	6.4	5.5	7.3	6.1	5.3	8.6	6.7	5.8
65-74	5.5	4.0	3.2	7.5	6.1	4.3	7.6	6.1	5.1	9.0	6.8	5.8	7.8	5.8	5.2	8.2	6.6	5.2	8.4	6.5	5.4	9.4	7.3	6.3
75+	5.9	5.2	4.2	7.1	6.5	5.0	10.5	8.3	6.5	11.4	9.6	7.3	9.3	8.0	6.6	9.7	8.5	7.0	10.6	9.2	7.0	11.3	9.3	7.9

Table 21. Mean least safe gap size (in meters) as a function of intersection geometry and driver age under control conditions (with no vehicle in the opposite turn bay).

Driver Age Group	Intersection Geometry			
	Full Positive	Partial Positive	Aligned	Partial Negative
25-45	126	128	124	109
65-74	148	146	144	128
75+	212	204	207	187

Table 22. Mean least safe gap size (in meters) as a function of intersection geometry, driver age, and oncoming vehicle type for control conditions (with no vehicle in the opposite turn bay).

Driver Age Group	Intersection Geometry							
	Full Positive		Partial Positive		Aligned		Partial Negative	
	Car	Truck	Car	Truck	Car	Truck	Car	Truck
25-45	126	126	126	129	115	134	104	114
65-74	143	154	142	150	127	160	116	139
75+	209	214	203	205	186	229	182	192



Oncoming Passenger Vehicle

Oncoming Semi-Tractor Trailer

Figure 32. Laboratory study mean least safe gap (in meters) for each age group as a function of left-turn lane geometry and oncoming vehicle type.

The further impact of oncoming vehicle speed on least safe gap judgments is documented in the results shown in Table 23. The mean values in this summary table generally show a decrease in this measure as oncoming vehicle speed increases. This finding—with isolated reversals under the two higher speed conditions—holds true for each driver age group, under each intersection geometry, and with both types of oncoming vehicles (passenger cars and heavy trucks). In addition, the magnitude of changes in minimum gap size for drivers of different ages across the various test conditions indicates that the oldest subjects were somewhat less sensitive to this variable. This mirrors results obtained in an earlier FHWA project (Staplin et al., 1993).

Statistical tests of these differences were performed using the General Linear Models procedure (PROC GLM) in Statistical Analysis System (SAS) software, due to missing data and resultant uneven cell sizes, which made use of the conventional ANOVA procedure problematic. The error terms employed in these analyses also deserve mention. Because of the repeated measures design in this experiment, each main effect was evaluated using the interaction of subjects-within-group as its error term, and for each interaction, the next higher interaction, nested within subjects, defined the error term (see Winer, 1962).

The GLM output revealed significant main effects of all variables: geometry [$F(3,192)=25.44; p<0.0001$]; age [$F(2,64)=15.49; p<0.0001$]; oncoming vehicle type [$F(1,64)=50.79; p<0.0001$]; and oncoming vehicle speed [$F(2,128)=16.83; p<0.0001$]. Consistent with trends identified in discussions of the descriptive statistics summarized above, these effects were localized as follows using the conservative Scheffé post hoc test with alpha fixed at 0.05. The effect of geometry resulted from the contrast between performance for the partial negative condition versus all other levels of this variable. The effect of age resulted from the comparison of the 75+ age group to the other two age groups, which were not significantly different from each other. The effect of oncoming vehicle speed resulted from the comparison of **each** level versus every other level, i.e., all levels were different from each other. There were only two levels of the oncoming vehicle type variable—car versus truck—which were significantly different from each other.

None of the two-way interactions of direct interest in this experiment reached statistical significance—i.e., neither geometry by age, speed by age, nor oncoming vehicle type by age. However, one three-way interaction was highly significant: geometry by age by type of oncoming vehicle [$F(23,512)=10.89; p<0.0001$]. This interaction was linked to the responses of the 75+ age group, with the aligned geometry, when the oncoming vehicle was a heavy truck. Specifically, while least safe gap size consistently increased with driver age and typically decreased for the partial negative geometry versus the other design alternatives, the largest difference in (mean) gap size, when oncoming vehicle type was taken into account, was demonstrated under the aligned geometry, for the 75+ age group.

Based on these statistically significant effects, which reinforce the patterns of results revealed through inspection of Tables 21 through 23, certain relative performance baselines can be established for the driver perceptual judgment at issue in this research. First, when focusing upon differences in geometry and their associated variations in sight lines and distances in the **absence** of opposite turning traffic, these results suggest that it is the **worst** visibility condition that is the key to observed performance differences in this experiment. However, drivers do not

Table 23. Mean least safe gap size (in meters) as a function of intersection geometry, driver age, oncoming vehicle type, and speed (km/h) for control conditions (with no vehicle in the opposite turn bay).

Driver Age	Intersection Geometry																							
	Full Positive						Partial Positive						Aligned						Partial Negative					
	Car			Truck			Car			Truck			Car			Truck			Car			Truck		
	56	72	88	56	72	88	56	72	88	56	72	88	56	72	88	56	72	88	56	72	88	56	72	88
25-45	143	122	112	144	119	116	144	115	119	144	124	118	124	114	107	144	130	128	111	103	97	123	110	108
65-74	167	135	127	161	161	141	159	129	137	165	147	137	139	115	128	182	151	148	125	108	116	153	132	133
75+	213	214	201	215	222	206	212	206	192	218	207	193	191	187	179	253	225	208	180	186	182	202	200	174

typically wait until the "last safe moment" to make a left turn across traffic, and under real-world traffic conditions there is commonly one or more vehicles—sometimes including heavy trucks—waiting to turn left from the opposite side of the intersection. In addition, the effects of age, and of oncoming vehicle type and speed as demonstrated in the "least safe gap" data make it essential to examine potential interactions with each independent variable when drawing conclusions about the effects of intersection geometry in the larger set of trials in the laboratory study where the simulated operating conditions were more realistic.

The frequencies with which subjects accepted unsafe gaps under each test condition are summarized as percentages in Tables 24 through 29. These data reflect counts of events where subjects continued to activate the trigger device, indicating a judgment that it was safe to proceed with a left turn, at a distance **less than** a threshold value. This is a highly conservative criteria, since it allows for neither braking by the opposing vehicle, nor any swerving to avoid collision with a late-turning driver.

The threshold values were calculated by multiplying the oncoming vehicle's speed by the time required for the turning driver to clear its path. In the field study (which is described in a subsequent section of this report), four left-turn lane geometries were selected for observation in Arlington, Virginia. These included: (1) a 0.91-m (3-ft) negative offset where drivers crossed three lanes of opposing traffic and a parking lane; (2) a 1.8-m (6-ft) positive offset where drivers crossed three lanes of opposing traffic and a parking lane; (3) a 0-m (0-ft) offset (aligned), where drivers crossed two lanes of opposing traffic; and (4) a 4.3-m (14-ft) negative offset, where drivers crossed two lanes of opposing traffic, plus the opposite left-turn lane. Intersection clearance time for drivers who had positioned themselves within the intersection while waiting to turn left was measured for each location, defined as the time a driver began making the left turn until the left turn was completed and the driver had cleared the intersection. Left-turn maneuvers were observed for between 30 and 36 older drivers at each intersection. A three-factor ANOVA conducted on these clearance time data indicated that there were no significant effects of age, gender, or location on drivers' abilities to accelerate and complete a left-turn maneuver. Most importantly, the mean clearance time for the older drivers at **each** intersection was 3.4 s. It appears, therefore, that drivers—including older drivers—accelerate to clear an intersection faster, the more lanes there are to cross; this behavioral adaptation suggests that intersection clearance times will evidence only minimal variability **within an age cohort**, across differing geometry. Based on these results, a representative intersection clearance interval for older drivers of 3.4 s was assumed for these analyses.

The analyses for which results are reported in Tables 24 through 29 were blocked according to the type of vehicle in the opposite turn-lane queue—passenger car versus semi-tractor trailer. Descriptive statistics and chi-square (χ^2) tests of differences between observed versus expected counts of these events are reported below.

Table 24 summarizes subjects' responses as a function of intersection geometry and driver age, where the vehicle in the opposite turn bay was a passenger car; the responses made when a heavy truck was in the opposite turn lane are summarized in Table 25. The most obvious effect apparent in these results is the marked increase in percentage of unsafe gaps accepted by the age 75+ subject group. This trend is consistent across both tables. The influence of geometry appears to vary by driver age group, however, and according to whether there is a passenger car versus a heavy truck in the opposite left-turn lane. With a heavy truck waiting across the intersection to turn left, the partial negative geometry resulted in elevated percentages of unsafe gaps accepted, for all age groups. This is not surprising; this combination of factors describes the worst visibility for the driver of oncoming traffic. When a passenger car was in the opposite turn lane, the geometries providing the **best** visibility of oncoming traffic—i.e., the full positive and partial positive geometries—produced relatively higher event counts, but only for the younger drivers. For the young-old and old-old drivers, the percentage of unsafe gaps remained highest for the partial negative geometry.

Table 24. Percentages of unsafe gaps accepted as a function of intersection geometry and driver age, with a passenger car in the opposite turn bay.

Driver Age Group	Intersection Geometry			
	Full Positive	Partial Positive	Aligned	Partial Negative
25-45	5.7	5.6	4.2	4.2
65-74	3.9	4.4	3.3	4.8
75+	14.5	15.3	14.5	19.7

Table 25. Percentages of unsafe gaps accepted as a function of intersection geometry and driver age, with a semi-tractor trailer in the opposite turn bay.

Driver Age Group	Intersection Geometry			
	Full Positive	Partial Positive	Aligned	Partial Negative
25-45	4.9	4.9	2.6	8.1
65-74	3.9	3.7	2.8	7.3
75+	13.0	13.7	15.0	20.1

Tables 26 and 27 summarize the responses for this measure when the type of oncoming vehicle **and** the vehicle in the opposite turn queue (passenger car versus heavy truck) are taken into account. These data indicate the same clear influence of driver age, showing that percentages of unsafe gaps accepted by subjects age 75+ were dramatically higher than for both of the other groups tested. The effect of geometry was again most apparent for the older driver groups, with the partial negative geometry resulting in the highest percentages of unsafe gaps accepted; this was most pronounced when a heavy truck was the vehicle in the opposite left-turn lane. The likelihood for an unsafe gap to be accepted if the oncoming vehicle was a passenger car versus a heavy truck was roughly equivalent across geometry.

Table 26. Percentages of unsafe gaps accepted as a function of intersection geometry, driver age, and oncoming vehicle type, with a passenger car in the opposite turn bay.

Driver Age Group	Intersection Geometry							
	Full Positive		Partial Positive		Aligned		Partial Negative	
	Car	Truck	Car	Truck	Car	Truck	Car	Truck
25-45	5.5	5.9	5.1	6.3	4.2	4.2	3.1	5.8
65-74	4.1	3.7	4.4	4.3	3.5	3.1	4.6	5.0
75+	15.3	13.3	16.0	14.2	14.0	15.1	20.2	19.1

Table 27. Percentages of unsafe gaps accepted as a function of intersection geometry, driver age, and oncoming vehicle type, with a semi-tractor trailer in the opposite turn bay.

Driver Age Group	Intersection Geometry							
	Full Positive		Partial Positive		Aligned		Partial Negative	
	Car	Truck	Car	Truck	Car	Truck	Car	Truck
25-45	4.7	5.2	5.4	4.3	2.4	2.7	8.5	7.8
65-74	4.0	3.8	4.0	3.5	2.8	2.9	8.0	6.5
75+	12.4	13.7	13.4	14.0	15.5	14.5	19.0	21.2

The speed of the oncoming vehicle is taken into account in the data summarized in Tables 28 and 29, where a passenger car and a heavy truck, respectively, occupy the opposite left-turn storage lane. These findings, of course, reflect the exaggerated percentages of unsafe gaps accepted by the 75+ age group, as already noted; however, other trends are apparent as well. Increasing the speed of the oncoming vehicle produced a regular increase in these event counts, **except** for the oldest age group, whose elevated rates of unsafe gap acceptance remained essentially the same regardless of oncoming vehicle speed, for either type of oncoming vehicle. Some evidence of a trend toward higher event counts when cars were the oncoming vehicle versus heavy trucks can also be seen, particularly at the highest oncoming vehicle speed, for the oldest age group.

Table 28. Percentages of unsafe gaps accepted as a function of intersection geometry, driver age, oncoming vehicle type, and speed (km/h), with a passenger car in the opposite turn bay.

Driver Age	Intersection Geometry																							
	Full Positive						Partial Positive						Aligned						Partial Negative					
	Car			Truck			Car			Truck			Car			Truck			Car			Truck		
	56	72	88	56	72	88	56	72	88	56	72	88	56	72	88	56	72	88	56	72	88	56	72	88
25-45	0.8	6.3	7.9	1.2	7.8	7.5	1.9	5.3	7.1	3.4	6.6	8.1	0.9	5.0	5.8	1.2	3.8	6.4	0.9	3.0	4.5	2.5	7.0	7.2
65-74	1.0	4.9	5.4	2.4	3.0	5.2	2.7	4.1	5.8	2.6	4.9	5.0	2.1	3.1	4.7	2.2	2.6	4.0	3.5	3.9	5.9	3.0	5.1	6.4
75+	19.7	15.2	12.6	16.7	13.0	11.3	21.0	15.5	13.3	19.1	13.4	11.7	18.6	13.7	11.3	20.0	14.3	12.5	26.9	20.2	15.8	25.9	18.7	14.7

Table 29. Percentages of unsafe gaps accepted as a function of intersection geometry, driver age, oncoming vehicle type, and speed (km/h), with a semi-tractor trailer in the opposite turn bay.

Driver Age	Intersection Geometry																							
	Full Positive						Partial Positive						Aligned						Partial Negative					
	Car			Truck			Car			Truck			Car			Truck			Car			Truck		
	56	72	88	56	72	88	56	72	88	56	72	88	56	72	88	56	72	88	56	72	88	56	72	88
25-45	2.3	4.4	6.2	1.8	5.9	6.9	1.6	5.9	7.2	0.8	4.6	6.3	0.2	2.8	3.4	0.2	2.6	4.4	3.3	7.3	12.2	3.0	8.2	10.5
65-74	2.2	3.7	5.3	2.1	4.2	4.7	3.1	3.7	4.7	2.3	3.6	4.1	2.1	2.7	3.3	2.1	2.7	3.4	2.8	6.7	11.9	3.2	5.0	9.8
75+	17.2	12.3	9.8	18.3	14.1	10.4	17.5	14.3	10.5	18.0	13.8	11.6	21.6	16.3	11.3	20.0	14.4	11.1	26.1	20.0	14.1	28.2	21.0	16.9

The data reported above are interesting because of an apparent contradiction with other research showing younger drivers to be more capable than older drivers in perceptions of speed and distance relationships to judge gaps ahead of oncoming traffic, when waiting to turn left at intersections (Staplin, Lococo, and Sim, 1993). The stimulus properties differ significantly between these respective measurements, however. In the former research, the target was continuously visible from the time it was detected as a point source in the distance, and guessing about its position was presumably not a factor in subjects' judgments. In the present analysis, the target was occluded by a blocking vehicle in the opposite turn lane, and subjects frequently made gap judgments with partial or no visibility of the oncoming through vehicle. The gap judgments in Staplin et al. (1993) were thus based much more explicitly on perceptual processes, while differences in the present analysis also reflect contrasts between subjects' risk-taking and risk-acceptance (i.e., motivational) states.

Chi-square tests were performed on these data at three levels: (1) sorted only by type of vehicle in the opposite turn lane; (2) sorted by opposite turn-lane vehicle type and oncoming vehicle type; and (3) sorted by opposite turn-lane vehicle type, oncoming vehicle type, and oncoming vehicle speed. In all cases, 2-way contingency tables were constructed containing 12 cells each, i.e., 4 geometries by 3 driver age groups. These tests were performed using SAS, which determined the observed and expected counts of unsafe gaps accepted by subjects within each driver age group, for each intersection geometry. The chi-square two-way contingency tables are presented in Appendix B.

At analysis level 1, the χ^2 test statistic was significant at $p<0.016$ ($\chi^2=15.6$; df=6) when a car was in the opposite left-turn lane, and at $p<0.0001$ ($\chi^2=35.2$; df=6) when a heavy truck was in the opposite left-turn lane. Both outcomes reflect the disproportionately high number of unsafe gaps accepted by the 75+ age group under the partial negative geometry. At analysis level 2, a significant test outcome was found for the conditions where a car was in the opposite turn lane and a car was the oncoming vehicle ($\chi^2=14.3$; df=6; $p<0.027$), and where a heavy truck was in the opposite turn lane and a car was the oncoming vehicle type ($\chi^2=27.7$; df=6; $p<0.0001$). For the stronger effect (heavy truck in opposite turn lane), rates of unsafe gap acceptance were demonstrably higher for the oldest subjects, and for the partial negative geometry. For the weaker effect (passenger car in opposite turn lane), the exaggerated event counts for the 75+ age group primarily accounted for the significant test statistic, as no consistent trends across geometry could be found. At analysis level 3, only a single test statistic reached significance—for the conditions where a heavy truck was in the opposite left-turn lane, and a car was the oncoming vehicle, traveling at the highest speed ($\chi^2=16.8$; df=6; $p<0.01$). Under these conditions, the 75+ age group again demonstrated the highest rates of unsafe gap acceptance, and event counts were consistently the highest for the partial negative geometry.

Analysis of the mean safety ratings showed a significant effect of geometry, with the geometries affording the best visibility of oncoming traffic perceived as significantly more safe than those providing poorer visibility. Table 30 shows how left-turning drivers perceived the safety of turning movements under each geometry, collapsed across trials where a passenger car versus a heavy truck was in the opposite turn lane. The safety ratings are then broken out according to type of vehicle in the opposite turn lane in Tables 31 and 32. Inspection of these tables reveals an extremely well-ordered pattern of results: the geometries affording superior visibility of oncoming traffic were perceived to be safer than those affording poorer visibility.

Table 30. Mean safety ratings on seven-point bipolar scale (1=most safe; 7=least safe) as a function of intersection geometry and driver age, without regard to type of vehicle in the opposite turn bay.

Driver Age Group	Intersection Geometry			
	Full Positive	Partial Positive	Aligned	Partial Negative
25-45	2.55	2.68	4.34	5.27
65-74	3.41	3.67	4.68	5.24
75+	4.05	4.15	5.06	5.29

Table 31. Mean safety ratings on seven-point bipolar scale (1=most safe; 7=least safe) as a function of intersection geometry and driver age, with a passenger car in the opposite turn bay.

Driver Age Group	Intersection Geometry			
	Full Positive	Partial Positive	Aligned	Partial Negative
25-45	2.53	2.64	3.73	4.85
65-74	3.35	3.55	4.20	4.96
75+	3.76	4.25	4.85	5.25

Table 32. Mean safety ratings on seven-point bipolar scale (1=most safe; 7=least safe) as a function of intersection geometry and driver age, with a semi-tractor trailer in the opposite turn bay.

Driver Age Group	Intersection Geometry			
	Full Positive	Partial Positive	Aligned	Partial Negative
25-45	2.58	2.73	4.95	5.68
65-74	3.48	3.80	5.16	5.52
75+	4.30	4.06	5.27	5.34

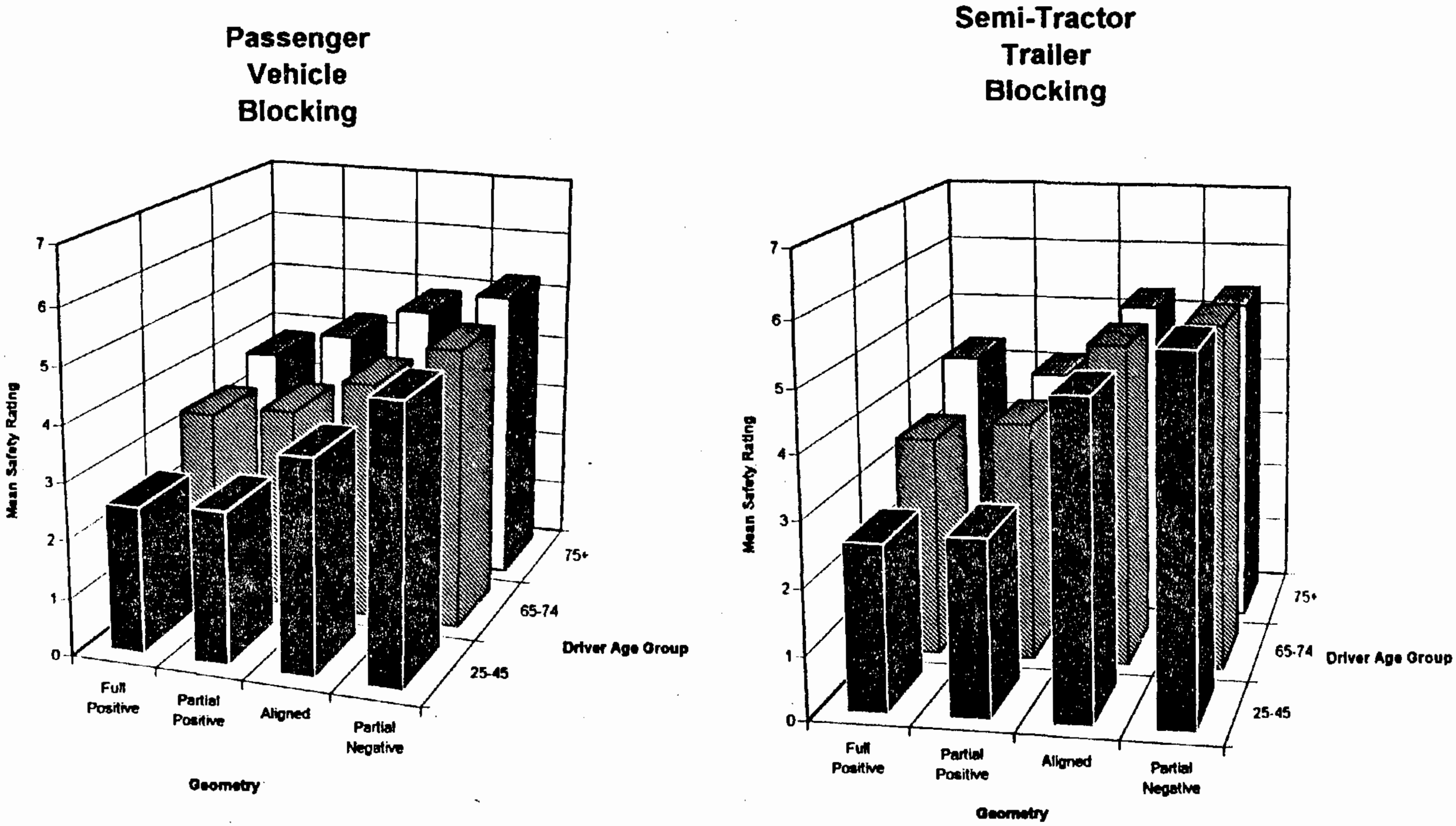
The partial negative geometry consistently received the lowest mean safety rating, and the positive offset geometries were consistently rated the highest in safety. An influence of driver age could also be discerned, such that older drivers typically generated lower safety ratings than younger drivers, but this effect was mitigated though an apparent "floor effect" under the worst (least safe) geometry—i.e., **all** subjects responded with low ratings under the partial negative geometry condition. An interaction of the age and geometry variables is suggested by this pattern of safety ratings. Mean safety ratings (1=most safe; 7=least safe) are presented in Figure 33 as a function of geometry, driver age, and blocking-vehicle type.

Tables 33 and 34 further examine these subjective responses, taking into account the speed of the oncoming vehicle in each trial. While the trend in these data is less obvious, a general finding of lower safety ratings when speed increases is apparent across the other variables represented in these tables, particularly when the lowest speed is compared to the two higher speeds. Interactions between oncoming vehicle speed, and intersection geometry and driver age are less apparent; however, it may be noted that a reduction in perceived safety with higher oncoming vehicle speed **and** as a function of increasing driver age is most clearly demonstrated for those geometries with the **best** visibility of approaching traffic (full positive and partial positive offset conditions). Thus, oncoming vehicle speed appears to influence subjects' responses in a consistent manner—i.e., to produce lower safety ratings—but potential interactions of this variable with other factors are less clear.

The PROC ANOVA in SAS tested the significance of these differences in the safety rating data. The following outcomes were revealed for tests where data were analyzed without regard to the type of vehicle in the opposite turn lane. Significant main effects of geometry [$F(3,192)=60.58$; $p<0.0001$] and of oncoming vehicle speed [$F(2,128)=13.65$; $p<0.0001$] were demonstrated, plus a significant interaction between geometry and driver age [$F(6,192)=3.20$; $p<0.005$]. As described earlier, due to the repeated-measures design employed in this experiment, the ANOVA model statements within SAS were modified to use subjects-within-group as the error term to test the between-subjects factor (driver age), and the interaction of subjects with geometry-nested-within-group as the error term to evaluate the main effect of geometry (a within-subjects factor) and the geometry-by-age interaction.

Similar patterns of results were demonstrated when the data were sorted according to the type of vehicle in the opposite turn lane. With a passenger car blocking subjects' view of oncoming traffic, main effects of geometry [$F(3,192)=47.43$; $p<0.0001$] and of oncoming vehicle speed [$F(2,127)=7.65$; $p<0.0007$] were again found, but the geometry-by-age-group interaction noted above failed to reach significance. When a truck occupied the opposite turn lane, main effects at $p<0.0001$ were demonstrated for both geometry [$F(3,192)=57.55$] and oncoming vehicle speed [$F(2,128)=12.80$], and the geometry-by-age interaction was significant as well [$F(6,192)=4.30$; $p<0.0004$]. The assignments of error terms for these ANOVA's within SAS were the same as described above for the analyses of the control ("least safe gap" size) data.

A discussion of the findings of the laboratory study is deferred to the end of the description of the field study of alternative left-turn lane geometry, to allow for a comparison of the similarities and differences in the independent and dependent variables in the laboratory and field studies, and to synthesize the results to support conclusions and recommendations about the design of intersections to increase the safety and mobility of older drivers.



Passenger Vehicle Blocking

Semi-Tractor Trailer Blocking

Figure 33. Laboratory study mean safety ratings on a seven-point bipolar scale (1=most safe; 7=least safe) as a function of intersection geometry, driver age, and blocking vehicle type.

Table 33. Mean safety ratings on seven-point bipolar scale (1=most safe; 7=least safe) as a function of intersection geometry, driver age, and speed (km/h), with a passenger car in the opposite turn bay.

Driver Age	Intersection Geometry											
	Full Positive			Partial Positive			Aligned			Partial Negative		
	56	72	88	56	72	88	56	72	88	56	72	88
25-45	2.50	2.45	2.64	2.59	2.68	2.64	3.14	4.18	3.86	4.59	4.91	5.05
65-74	3.36	3.32	3.36	3.16	3.60	3.88	3.96	4.24	4.40	4.76	4.88	5.24
75+	3.48	4.00	3.82	4.13	4.35	4.27	4.57	4.77	5.23	5.09	5.39	5.27

Table 34. Mean safety ratings on seven-point bipolar scale (1=most safe; 7=least safe) as a function of intersection geometry, driver age, and speed (km/h), with a semi-tractor trailer in the opposite turn bay.

Driver Age	Intersection Geometry											
	Full Positive			Partial Positive			Aligned			Partial Negative		
	56	72	88	56	72	88	56	72	88	56	72	88
25-45	2.32	2.55	2.86	2.68	2.73	2.77	4.68	4.91	5.27	5.68	5.77	5.59
65-74	3.12	3.60	3.72	3.64	3.72	4.04	5.00	5.20	5.28	5.40	5.48	5.68
75+	3.61	4.62	4.57	3.91	4.22	4.05	4.65	5.55	5.64	5.22	5.52	5.27

Field Study

Independent Variables. Four left-turn lane offset geometries 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 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.
(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. The four intersections are diagrammed in Figure 34.

Dependent Variables/Measures of Effectiveness. 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.[2] 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.

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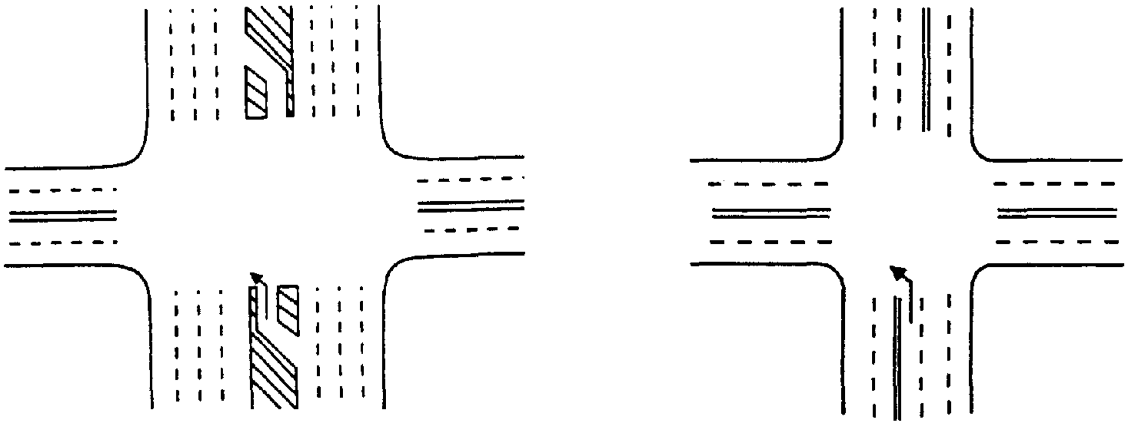
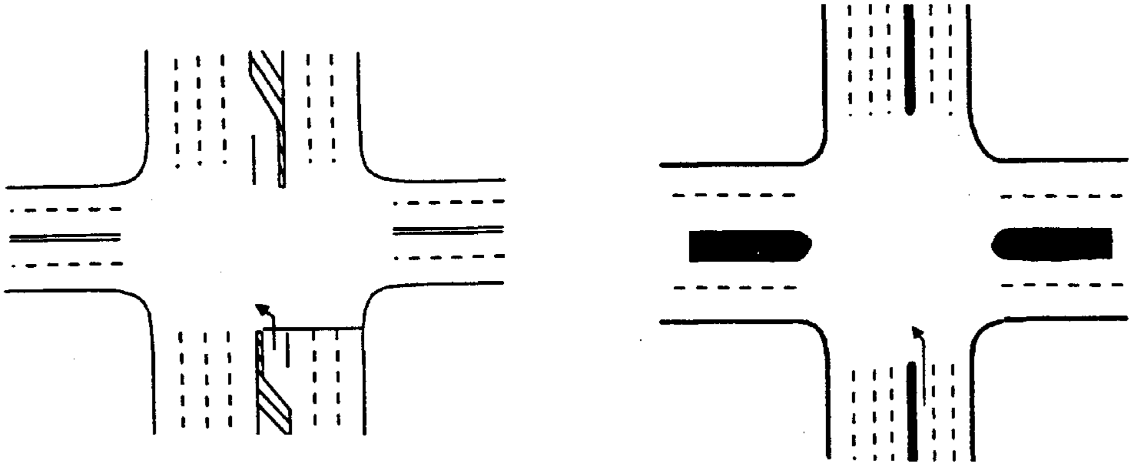
[2] It may be noted that PROBIT and LOGIT differ primarily in that PROBIT relies on a maximum likelihood estimation approach, while LOGIT uses a weighted least-squares approach for curve-fitting (regression). However, PROBIT and LOGIT are both examples of the same general class of modified regression models designed especially for use with qualitative data (see Goodman, 1978), such as the dichotomous "safe" versus "unsafe" gap acceptance decisions performed by subjects in the laboratory and field studies. In each of these project activities, a curvilinear response function describes the probability that the dependent variable assumes one or the other of its dichotomous values (gap acceptance or gap rejection) in relation to repeated observations along the stimulus dimension (target separation distance) quantified on the abscissa. According to a textbook comparison of the maximum likelihood estimators for error versus the estimates provided by the least-squares method, for the sample sizes used and parameters derived in the present analyses, LOGIT and PROBIT will yield identical results (Neter and Wasserman, 1974). In this research the co-principal investigator deemed the use of LOGIT most appropriate to derive critical gap measures in the field study data because: (1) this approach is most commonly reported in the traffic engineering technical literature where related analyses are cited, and (2) the model's assumptions regarding the type and number of observations (sample size) were met. PROBIT was deemed the more useful approach to derive critical gap size in the laboratory data analysis, however, because in SAS this procedure allowed greater flexibility with respect to missing values. In the laboratory, continuous gap judgments were performed under conditions where the target vehicle first appeared at each of nine different (discrete) separation distances from the observer (i.e., 30.5 m to 274.3 m [100 ft to 900 ft], in 30.5-m [100-ft] increments). The PROBIT procedure in SAS allowed the generation of a much larger set of dummy values representing intermediate distances between these nine discrete separation values before performing the curve-fitting analysis culminating in the probability functions in Figure 29.



(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 34. Alternative intersection geometries evaluated in the field study.

(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.

Test Sample. 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. The criteria for subject selection were: (1) valid driver's license, (2) proof of automobile insurance (to ensure that subjects drive on a regular basis and are financially responsible in case an incident occurred during the study), and (3) willingness to sign a liability agreement stating that they volunteered to participate in the study without any kind of pressure. All subjects were volunteers that were paid $25 to participate in the study, and all were recruited through local newspapers, senior citizen publications, retirement homes, and face-to-face contacts with drivers at three driver license renewal centers. Table 35 presents the driver and vehicle characteristics of study participants.

Methodology. In the field study, 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- 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.

Table 35. Characteristics of left-turn field study test sample.

Variable	Driver Age Group					
	25-45		65-74		75+	
	Female	Male	Female	Male	Female	Male
Number of Participants	17	16	17	20	16	14
Mean Age	31.9	34.2	67.6	67.8	76.8	79.1
Mean Driving Experience (Years)	15.2	17.5	46.4	42.2	44.6	62.3
Mean No. Trips/Week	12.1	19.6	8.9	12.2	9.3	12.1
Mean No. Miles Driven/Week	202.4	195.3	94.1	157.8	110.0	190.4
Mean Automobile Power (Cylinders)	5.2	5.1	5.8	5.8	4.9	6.3
Automobile Dimensions (Feet)						
Mean Lateral Wheelbase	4.8	4.8	4.9	5.0	4.8	5.0
Mean Longitudinal Wheelbase	8.7	8.8	8.9	9.2	8.4	8.9

1 mi = 1.61 km
1 ft = 0.305 m

Results. The data included in this analysis 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 36 shows the critical gap values (in seconds) and the number of gaps accepted for each age-gender group at the four study locations. The trend is that older drivers have larger critical gap values at all locations. Also, all age-gender groups have larger values at the 4.3-m (14-ft) negative offset location.

Table 36. 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-Foot Offset	-3-Foot Offset	0-Foot Offset	+6-Foot 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

A three-factor Analysis of Variance (ANOVA) employed the General Linear Models procedure in SAS (PROC GLM).[3] Age [F(2,6)=62.50; $p<0.0001$] and geometry [F(3,6)=6.05; $p<0.0302$] were the only significant main effects. None of the two-way interactions reached statistical significance. A Tukey test 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. A Tukey test conducted on the geometry factor (offset) showed that the -0.91-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).

Figure 35 presents the mean left-turn critical gaps (in seconds) obtained in the field study as a function of left-turn lane geometry and driver age group. It is important to note that critical gap data were only computed for those subjects who positioned their vehicles within the intersection while waiting to turn and who made their turns while there was at least one vehicle in the opposite turn lane.

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[3] For this and every other analysis conducted on repeated measures data in this research, each main effect was evaluated using the interaction of subjects within group as its error term, and for each interaction, the next higher interaction—nested within subjects—defined the error term (see Winer, 1962).

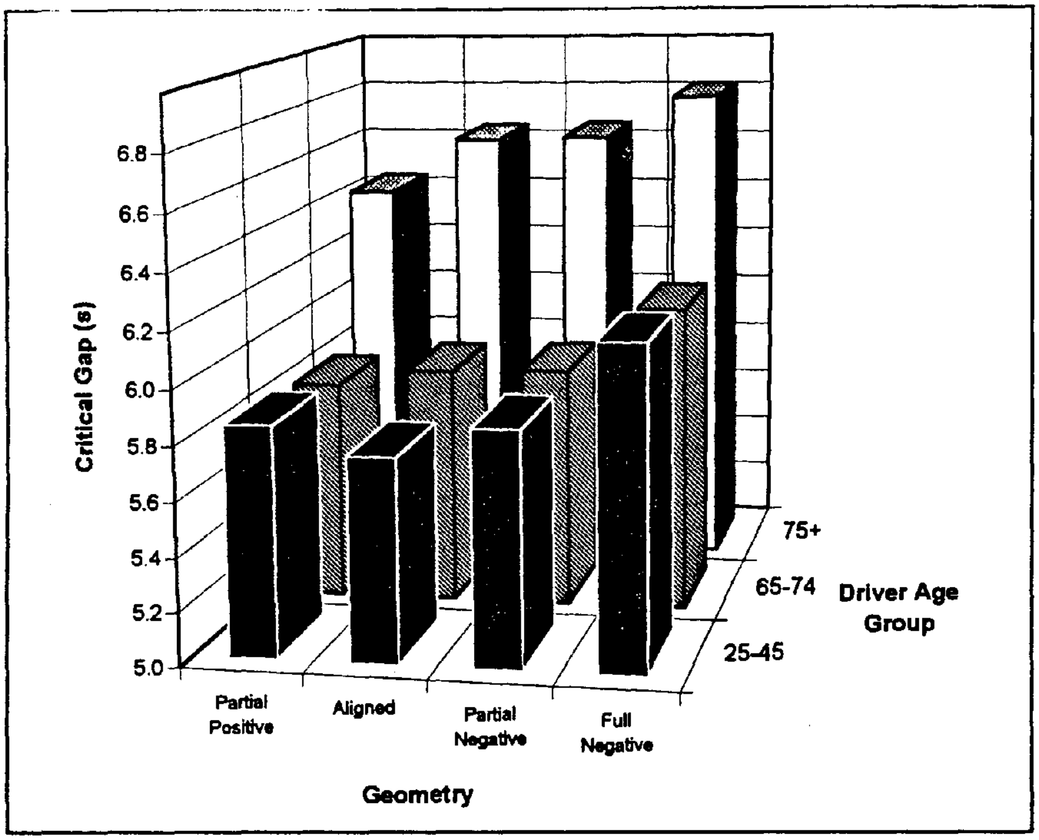


Figure 35. Field study mean left-turn critical gaps (in seconds) as a function of left-turn lane geometry and driver age group.

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 37 shows the sample size and the mean and standard deviation clearance time values (in seconds) for each age-gender group at the four study locations. 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) using the SAS GLM procedure 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. This absence of differences is notable, providing support for the assumption of a fixed clearance interval (3.4 s) for calculations of unsafe gap acceptance rates in the analysis of laboratory study data. The mean clearance time across location, age, and gender was 3.28 s. Although the mean clearance time for the 75+ age group was 3.4 s, which was slightly longer than those of the two younger groups, the differences were less than 0.15 s in most cases.

Table 37. Sample size (n), mean ($\bar{x}$), and standard deviation (s.d.) of 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				All Sites
			-14-Foot Offset	-3-Foot Offset	0-Foot Offset	+6-Foot Offset	
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	123	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 time data for unpositioned vehicles are shown in Table 38. 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 39 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 38. Sample size (n), mean ($\bar{x}$), and standard deviation (s.d.) of 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				All Sites
			-14-Foot Offset	-3-Foot Offset	0-Foot Offset	+6-Foot Offset	
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	27
		$\bar{x}$	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	25	28	30	26	109
		$\bar{x}$	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

Next, the analysis of left-turn conflicts was limited, because only two such events occurred in the study, both at the -4.3-m (-14-ft) offset location. In the first conflict, an older test subject slowly positioned himself and crossed the adjacent conflicting lane. A conflict vehicle was required to stop completely to avoid a collision. In the second occasion, a young/middle-aged (male) driver did not stop before initiating the maneuver, and entered the intersection at high speed. The conflict vehicle was required to slow down severely to avoid collision. The younger driver explained that upon his approach, he judged that the conflict vehicle was far enough from the intersection for him to make the turn. No statistical analysis could be conducted on this measure, due to the limited occurrence of near-misses.

Table 39. Comparison of clearance times obtained in the field study with AASHTO *Green Book* values used in sight distance calculations.

Measure	Vehicle Location	Left-Turn Lane Geometry			
		-14-Foot Offset	-3-Foot Offset	0-Foot Offset	+6-Foot 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

Analysis of the lateral positioning data showed that all age-gender groups performed comparably. The SAS GLM procedure indicated that geometry was the only significant variable [F(3,119)=550.17; p<0.0001]. A Tukey test for multiple comparisons showed that except for the +1.8-m (+6-ft) offset and the aligned location, all geometries showed lateral position values that were significantly different from each other—the more negative the offset, the farther drivers moved to the left in order to see oncoming traffic in the opposing lanes. Across age-gender groups, the mean lateral position values 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. Thus, under the most negative offset condition, drivers crossed the lane boundary by almost 1.5 m (5 ft); under partial negative offset conditions, they positioned themselves within 2.54 cm to 5.08 cm (1 to 2 in) of the lane boundary; and under the remaining conditions, a larger margin of safety was allowed.

Analysis of the longitudinal positioning data showed that geometry was the only significant variable in the GLM analysis [F(3,119)=12.80; p<0.0001], and none of the interactions were significant. 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 -0.91-m (-3-ft) offsets had the same effect on the longitudinal positioning of drivers making the left-turn maneuver. The mean longitudinal positions were: 6.0 m (19.6 ft) for the full negative offset; 7.22 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 36 depicts the longitudinal and lateral distances used to define vehicle position.

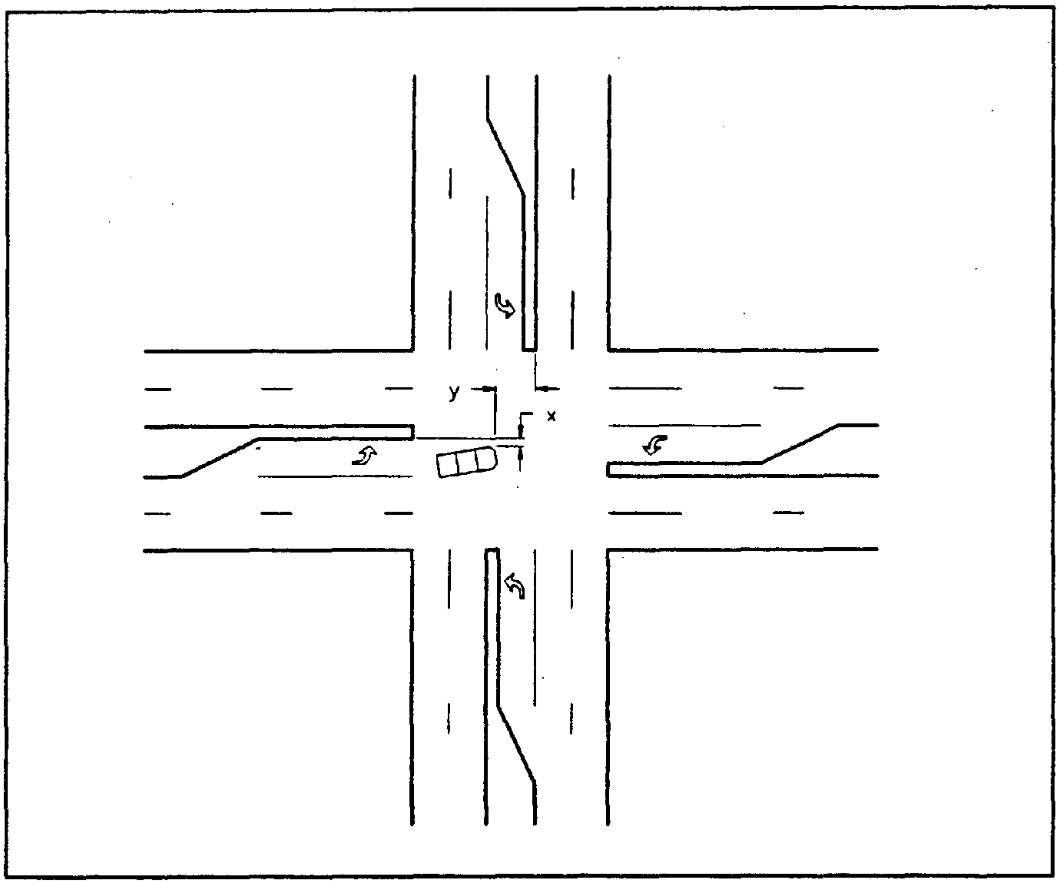


Figure 36. Longitudinal and lateral distances used to define vehicle position in the field study.

Analysis of the data describing the percentage of drivers who chose to pull into the intersection to position themselves before making a left turn, while a vehicle occupied the opposite left-turn lane, found that only age and gender were significant; location did not affect the positioning percentages. The percentage of subjects who chose to position themselves was lower for the old-old drivers than for the two younger driver age groups. Approximately two-thirds of the old-old drivers (68 percent) chose to position themselves, compared to 84 percent of the young-old drivers and 92 percent of the young/middle-aged drivers. The differences between the three age groups were significant [$F(2,6)=175.19; p<0.0001$]. Additionally, males positioned themselves significantly more often than females [$F(1,6)=18.0; p<0.0054$]. Across driver age groups, females positioned themselves 79 percent of the time, compared to males who positioned themselves 84 percent of the time. Thus, older drivers and female drivers were less likely than younger drivers and male drivers to position their vehicles within an intersection when waiting to make a left turn. Although the location with the -4.3-m (-14-ft) offset had the highest

highest percentage of subjects who positioned themselves, there was no consistent pattern between left-turn offset and the positioning percentages.

After each left-turn maneuver was executed, drivers were asked to choose one of three responses to the following question: "Based on your experience making left turns at other intersections, under similar traffic conditions, the turn at this intersection was (a) more difficult than usual, (b) easier than usual, or (c) no different—about the same as usual." Overall, drivers responded that making left turns at the +1.8-m (+6-ft) offset location was more difficult than usual compared to other locations, followed by the -4.3-m (-14-ft) offset location and the aligned location. The location with the -0.91-m (-3-ft) offset was rated as easier or about the same in level of difficulty. It may be noted that this is a very common offset found between opposite left-turn lanes, whereas both the +1.8-m (+6-ft) offset and the -4.3-m (-14-ft) offset are more uncommon. Although chi-square tests showed no significant associations between age, gender, and location, it is interesting to note that with respect to location, the young-old males most frequently indicated the -4.3-m (-14-ft) offset to be "more difficult than usual" and old-old females most frequently found the 0-m (0-ft) offset to be "more difficult than usual." Old-old males believed that both the 0-m (0-ft) and -4.3-m (-14-ft) offset locations were "more difficult than usual."

At the completion of the left-turn study, subjects were asked to respond to the following four questions regarding the perceived level of safety of intersection traffic control signal displays.

(1) Which of the following statements do you agree with the most concerning the safety of different types of left-turn traffic displays: (a) "A green arrow is safer than a green ball, and should always be provided"; (b) "A green arrow is safer than a green ball, but I have no difficulty using a green ball to make a left turn"; or (c) "A green ball and a green arrow are the same to me."

(2) Which of the following statements do you agree with the most about the level of safety in making a left turn using a green ball: (a) "I feel it is usually safe to make a left turn using a green ball"; (b) "I feel it is usually dangerous to make a left turn using a green ball"; or (c) "I feel that it is safe at some intersections and dangerous at other intersections to make a left turn using a green ball."

(3) Of the following maneuvers at an intersection, which is the most stressful for you: (a) Making a left turn on a green ball; (b) Making a left turn on a green arrow; or (c) Making a right turn on red.

(4) Which of the following statements best describes your usual reaction when you are approaching an intersection and the light turns yellow: (a) "I usually continue on through the intersection"; or (b) "I usually stop at the intersection."

When drivers were asked to compare the relative safety of a green arrow and a green ball traffic signal indication, the majority of drivers (64 percent) believed that the green arrow was safer than the green ball, but they indicated that they did not have difficulty with the green ball. No association was found between a subject's response and his/her age or gender. When drivers were asked about the safety of making a left turn using a green ball (i.e., turning left during a permissive left-turn phase), the majority (81 percent) indicated that making a left-turn maneuver on the green ball was safe at some locations and dangerous at others. When drivers were asked to identify which of the following maneuvers was the most stressful for them: (1) making a left turn on a green ball, (2) making a left turn on a green arrow, or (3) making an RTOR, the vast majority (88 percent) indicated that making a left turn on the green ball was the most stressful maneuver at an intersection. When drivers were asked to indicate their usual reaction to a yellow signal indication (i.e., continue through the intersection or stop), almost one-half of young/middle-aged drivers indicated that they tend to continue through the intersection when they see the yellow indication. Only about 20 percent of the young-old drivers and less than 10 percent of the old-old drivers indicated that they continued through the intersection. In all age groups, the percentage of male subjects continuing through the intersection on the yellow was higher than for the female subjects.

Discussion

The following discussion reviews key findings and suggests possible explanations for and/or implications of the observed effects.

The principal **laboratory** study findings include: (1) smaller critical gap size for the full positive geometry than for the partial positive, aligned, or partial negative geometries; (2) significant main effects of driver age, geometry, oncoming vehicle type, and oncoming vehicle speed on mean least-safe gap judgments; (3) a 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; (4) disproportionately higher percentages of unsafe gaps accepted by the 75+ age group under the partial negative geometry, for both opposite left-turning vehicle types; (5) 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; and (6) a significant interaction between geometry and driver age on perceived safety, where all subjects responded with low ratings for the partial negative geometry; but the lowest safety ratings under this study condition were produced by older drivers.

The principal **field** study findings include: (1) 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; (2) a 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; (3) a significant effect 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; and (4) subjective responses to survey questions indicated 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 intersection maneuver.

One major difference in the "presentation" of the opposing lane of through traffic for the laboratory and field studies deserves mention because of important sight distance consequences. In the field study, drivers were allowed to position their vehicles within the intersection, thereby attenuating the effect of the primary independent variable (offset level). That is, a driver positioned within the intersection may obtain a view of oncoming through traffic for all geometries except the negative 4.3-m (14-ft) offset. This would tend to minimize performance differences across geometries in the field study. The findings from the field study indicate that many drivers will indeed position themselves within an intersection to provide the maximum sight distance before initiating a left turn, and, not surprisingly, performance differences were dramatically worse for the -4.3-m (-14-ft) offset situation, while the other three geometries showed relatively similar driver behavior. In the laboratory study, however, the position of the left-turning driver was held constant so that opposite left-turn lane geometry was the **only** variable influencing sight distance under a given operating condition, and results showed performance differences that were dramatically superior for the full positive offset geometry condition and worse for the other geometries where sight distance became progressively more restricted.

These differences in "stimulus presentation" that varied across experiments are critical to the present research objectives 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. This suggests that designers should focus on providing adequate sight distance for a driver **positioned at the stop bar**, if the overriding concern is to accommodate this user group.

Furthermore, in the analysis of the field study lateral positioning data, it was 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 (-0.91 m [-3 ft]) versus the partial positive offset and aligned geometries, suggesting a need for longer sight distance when intersections are even partially negatively offset. 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, which reinforces the notion that negative offsets do not provide adequate sight distances for opposite left-turning vehicles. 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) offset provides unrestricted sight distance when the opposite left-turning vehicle is a passenger car, and (2) a 1.06-m (3.5-ft) offset provides unrestricted sight distance when the opposite left-turning vehicle is a truck.

ALTERNATIVE PEDESTRIAN CROSSWALK CONFIGURATIONS

Laboratory Study

Independent Variables. Three independent variables were included in the laboratory study of alternative pedestrian 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, which included the presence or absence of a pedestrian refuge island, the width of the refuge island (1.8 m or 3.6 m [6 ft or 12 ft]), the number of refuge islands (1 or 2), and the crossing path distance (18.3 m, 20 m, or 22 m [60 ft, 65 ft, or 72 ft]). These varying crosswalk configurations are diagrammed in Figure 37. Driver ages were 25-45, 65-74, and 75+. Two levels of design walking speed were also studied: 0.9 m/s (3 ft/s) and 1.2 m/s (4 ft/s). Finally, the introduction of 0.9-m- (3-ft-) high yellow "delineator poles" at the borders of median islands was also included as a blocking variable in this study.

Dependent Variables/Measures of Effectiveness (MOE). The dependent measures included subjective ratings of safety and willingness to use the crosswalk under each intersection geometry, and an objective measure of mobility that was the amount of time after the beginning of the protected crossing phase that an individual remained willing to start to cross the intersection.

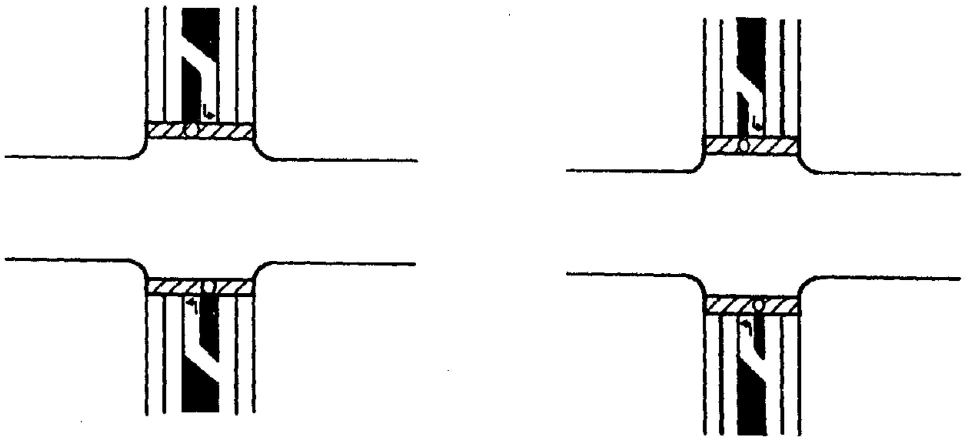
Test Sample. The identical subjects from the laboratory study of alternative left-turn lane geometry were recruited to provide 24 subjects in each of 3 age groups: *25-45, 65-74,* and *75+*. However, some attrition occurred between the two laboratory experiments, which made it necessary to replace a few individuals within each group. The numbers of replacement subjects recruited for the laboratory pedestrian study were two in the 25-45 age group, one in the 65-74 age group, and three in the 75+ age group. The demographics of the resulting sample are shown in Table 40.

Table 40. Characteristics of subjects recruited for the laboratory study of pedestrian crosswalk/median preferences.

Pedestrian Age Group	Number of Subjects	Number (%) of Males	Number (%) of Females	Mean Age	Median Age
25-45	21	10 (41)	11 (46)	34	33
65-74	23	12 (52)	11 (48)	68	67
75+	23	15 (65)	8 (35)	78	78

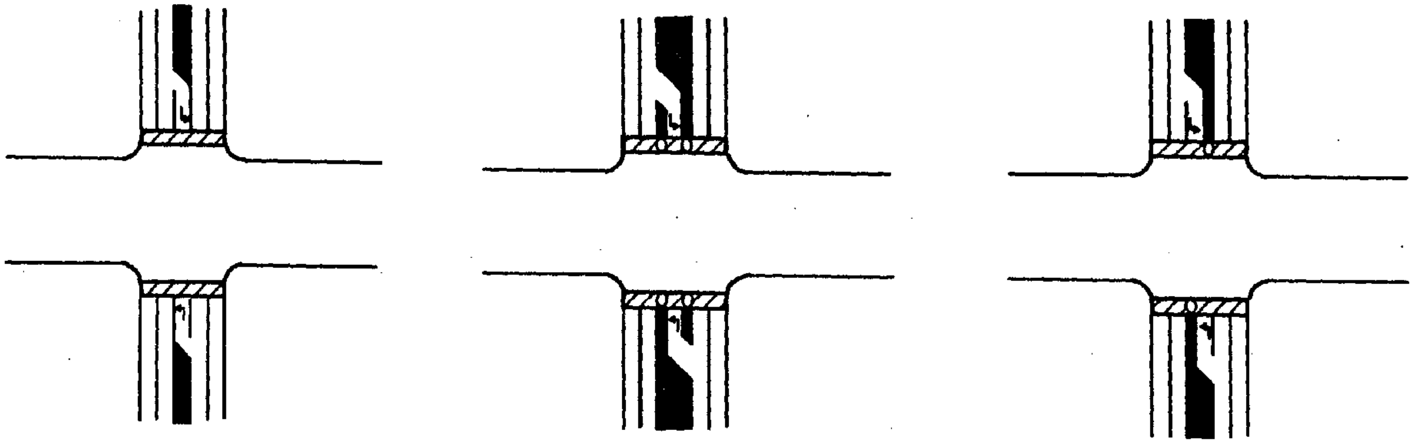
Assessments of subjects' visual capabilities demonstrated the same general performance characteristics by age group as reported for the earlier laboratory study. Two subjects age 75+ and one subject between the ages of 65 and 74 scored 20/60; all other subjects in each group demonstrated acuities of 20/40 or better, and all scored within normal ranges for contrast sensitivity.

Methodology. A repeated-measures design was used, such that all subjects generated data for all dependent measures, in all test conditions. A total of 18 test conditions were defined by the combination of within-subjects factors identified earlier: five intersection geometries, with



full positive offset geometry
islands: 1 (3.7 m wide)
intersection width: 6 lanes

partial positive offset geometry
islands: 1 (1.8 m wide)
intersection width: 5½ lanes



aligned geometry
islands: none
intersection width: 5 lanes

aligned geometry
islands: 2 (1.8 m wide each)
intersection width: 6 lanes

partial negative offset geometry
islands: 1 (1.8 m wide)
intersection width: 5½ lanes

Figure 37. Intersection geometries and associated crosswalk configurations evaluated in the laboratory study.

associated changes in the number, size, and location of median refuge islands; the presence or absence of median delineator poles; and two walking speeds, as shown in Figure 38. The delineator pole factor was absent for one geometry (aligned), which did not include a pedestrian refuge island. It may be noted that driver age was a between-subjects factor in this design.

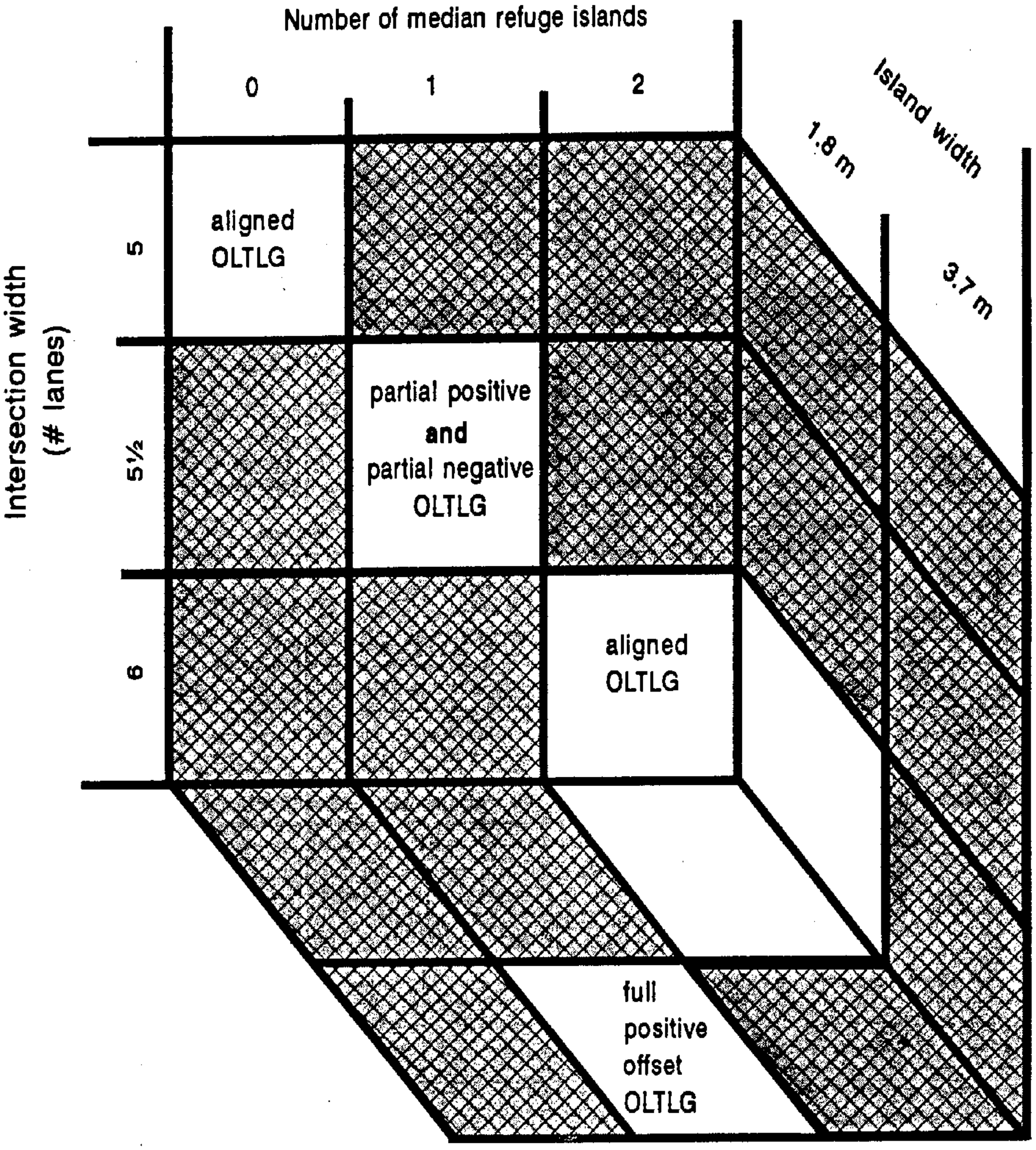
The apparatus included carousel slide projectors, a projection screen, and the trigger response device used in the earlier laboratory experiment. The personal computer (PC) used earlier to operate the simulator was used to create data files, through manual entry by the experimenter of subjects' verbal responses. Also, the PC was programmed to record timing data to measure the duration of subjects' trigger-pull responses for the objective MOE.

Data collection was performed on a one-subject-at-a-time basis, in a single laboratory session approximately 30 minutes long. Each subject was seated in a hard-backed chair 2.1 m (7 ft) from the projection screen, which displayed a pedestrian crosswalk scene. This resulted in a correct perspective view of the crosswalk from the vantage point of a pedestrian at the corner curb ready to step into the crosswalk.

The first exercise in this experiment required subjects to verbally explain their understanding of each phase of pedestrian control signal operation. The experimenter recorded the accuracy of these responses, then provided an "operational definition" of the protected phase, clearance interval, and prohibited phases of signal operation to all subjects, plus instructions for the initial task, as follows:

> *When you see the steady WALK indication it means that you are protected in the crosswalk and it is safe to cross the intersection. When you see the flashing DON'T WALK sign appear it means that you should not leave the curb if you have not already begun to cross the intersection; but if you are already partway across, you should continue and get to a safe location as soon as possible. When you observe the steady DON'T WALK sign you should not be in the crosswalk, because the light is about to turn green for intersecting traffic.*
>
> *In the study today you will see slides showing the view along the crosswalk from the perspective of a pedestrian standing on the curb waiting to cross an intersection. An oversized pedestrian signal will be superimposed on the scene. This will show the WALK and DON'T WALK phases which make up a crossing cycle. I will show you the crossing cycle length for this intersection that is consistent with current engineering standards. After watching the complete crossing cycle—the WALK display, through the flashing DON'T WALK interval, to its end with the steady DON'T WALK display—I will ask you to respond to a couple of questions regarding the crosswalk cycle which you just observed.*

The experimenter then proceeded with the first stimulus slide. Microprocessor control over the slide projector was used to achieve the steady and flashing indications. The crossing cycle length on each slide presentation was appropriate for assumed walking speeds of either 0.9 m/s (3 ft/s) or 1.2 m/s (4 ft/s), with the onset of the clearance interval indication gauged in accordance with current AASHTO guidelines (AASHTO, 1994). Slide presentations were made



Walking speed: All subjects in each age group provided **two** responses for all indicated cells in this matrix, corresponding to varying pedestrian signal timing for design walking speeds of 0.9 and 1.2 m/s, respectively.

Figure 38. Test conditions for laboratory study of pedestrian preferences for crosswalk/median design.

for each of the 18 test conditions in this fashion, counterbalanced (across geometry and walking speed) using a Latin-square type design. After each slide, subjects were asked:

> *Please choose a number from 1 to 5 to judge how safe or unsafe this crosswalk would be if you were a pedestrian and you observed the crosswalk cycle that you have just seen. The rating scale is as follows: 1 means extremely safe, 2 means moderately safe, 3 means you are neutral, 4 means moderately unsafe, and 5 means extremely unsafe.*

After the subject responded verbally with a number from 1 to 5, the experimenter asked the subject to choose one of the following statements to best represent his/her perception of the intersection shown in this slide: (1) "If I were a pedestrian, I **would** use this crosswalk," or (2) "If I were a pedestrian, I **would not** use this crosswalk." If a subject responded to the second question by stating that he/she would **not** use the crosswalk displayed on a given trial, the slide was then removed from the slide tray and excluded from use in the objective data collection exercise that followed. In addition, to complete the subjective data collection, each subject was asked to use his/her own words to elaborate on why he/she rated the crosswalk as extremely safe/moderately safe/neutral/ moderately unsafe/extremely unsafe. The subject's verbal free-response answer to this question was then manually recorded by the experimenter, and is presented in Appendix C.

The experimenter then delivered the instructions for the next part of the study, which employed the hand-held trigger (gaming device) used in the earlier laboratory study. As noted above, any intersection crosswalk configuration(s) that a given subject indicated in the first part of this experiment that he/she would **not** be willing to use was excluded from this objective data collection exercise. The instructions were as follows:

> *In this exercise, I want you to suppose you are approaching this intersection with the intention of crossing, and that you have not quite reached the curb when you see the WALK phase begin. I want you to let me know what is the last possible moment that you could reach the curb, remembering that the WALK phase has already begun, and still feel safe starting across this crosswalk. You will indicate this by squeezing the trigger. When I first show you the slide of the intersection with the WALK signal visible, you will* ***not*** *be squeezing the trigger, then at some point you will squeeze the trigger, which is the same as stepping off the curb. Again, when you squeeze the trigger you are indicating that you are now stepping off of the curb, at the last moment that you feel you still have enough time available in the crossing cycle to reach safety.*

<u>Results</u>. Results of the survey of participants' comprehension of pedestrian control signal operations, conducted prior to study commencement, are shown in Table 41. All subjects subsequently received an explanation of signal operations from the experimenter.

Tables 42 and 43 summarize the differences in subjects' willingness to use the various crosswalk configurations as pedestrians. Older subjects—the 65-74 age group more so than the 75+ age group—responded more frequently than subjects ages 25-45 that they would be unwilling to use one or more of the crosswalk designs, though these age differences were somewhat smaller when the high-visibility (yellow) delineator poles were added as a median design feature. An influence of geometry, operationalized in this experiment in terms of the specific crosswalk configurations, was less apparent, although inspection of these data reveals that the aligned intersection designs (both the no median design with crosswalk length of 18.3 m and the two-median design with a crosswalk length of 22 m) received the highest number of "unwilling to use" responses. The percentages of subjects who indicated that they would **not** be willing to cross the intersection as pedestrians is presented in Figure 39, as a function of crosswalk configuration and pedestrian age, for the 0.9-m/s (3-ft/s) and the 1.2-m/s (4-ft/s) walking speeds, under the no median delineator pole condition. If any conclusion can be supported by this pattern of findings, it may be that a single median refuge island is preferred over either no median—even when associated with a shorter overall crosswalk length—or two medians, which may add to the perceived distance and effort involved in traversing the intersection as a pedestrian. No clear pattern of differences solely as a function of the walking speeds modeled in this laboratory simulation could be discerned.

Table 41. Percentages of test sample demonstrating comprehension of pedestrian control signal operations before beginning the experiment.

Pedestrian Age Group	Male	Female
25-45	30	91
65-74	42	36
75+	40	100

Mean safety ratings for the various test conditions are reported in Tables 44 and 45. Based on the designs without median delineator poles—i.e., standard practice—the clearest trend emerging in these data is the relatively lower perceived safety level for the crosswalk configurations associated with the aligned geometry. No obvious influence of walking speed, as simulated in this experiment, could be discerned, and the addition of the delineator poles to the four out of five crosswalk configurations with medians also appeared to have only a very modest (negative) impact on subjects' ratings of safety. Finally, differences related to the age of subjects were mixed. The oldest (75+) group most often generated the **highest** safety ratings (lowest rating-scale values), except for isolated conditions in which the crossing cycle stimuli depicted the higher simulated walking speed. No interaction between age and geometry (crosswalk configuration) was readily apparent, with or without the presence of the yellow delineator poles as a median design element.

PROC ANOVA in SAS was used to test the statistical significance of differences on this measure, which were obtained for all subjects regardless of their willingness to use each of the crosswalk configurations as a pedestrian. The assignment of error terms was specified as appropriate for repeated-measures designs (see earlier discussion). Only a main effect of geometry (crosswalk configuration) was demonstrated in these analyses [$F(4,256)=4.31$; $p<0.0022$]. A Scheffé post hoc test localized the source of this effect to the contrast between the

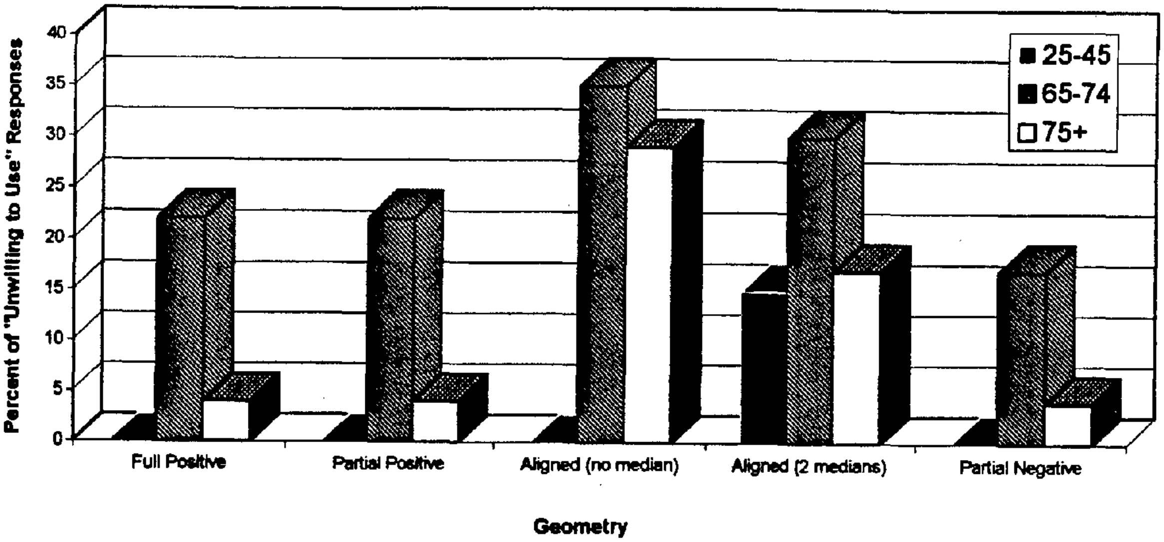
Table 42. Percentages of test subjects who indicated that they would not be willing to cross the intersection as pedestrians. [Median delineator poles were absent.]

	CROSSWALK CONFIGURATION									
	Full Positive		Partial Positive		Aligned (no median)		Aligned (2 medians)		Partial Negative	
Driver Age	0.9-m/s walking speed	1.2-m/s walking speed	0.9-m/s walking speed	1.2-m/s walking speed	0.9-m/s walking speed	1.2-m/s walking speed	0.9-m/s walking speed	1.2-m/s walking speed	0.9-m/s walking speed	1.2-m/s walking speed
25-45	0	0	0	0	0	0	15	25	0	0
65-74	22	17	22	22	35	39	30	9	17	13
75+	4	8	4	17	29	33	17	8	4	12

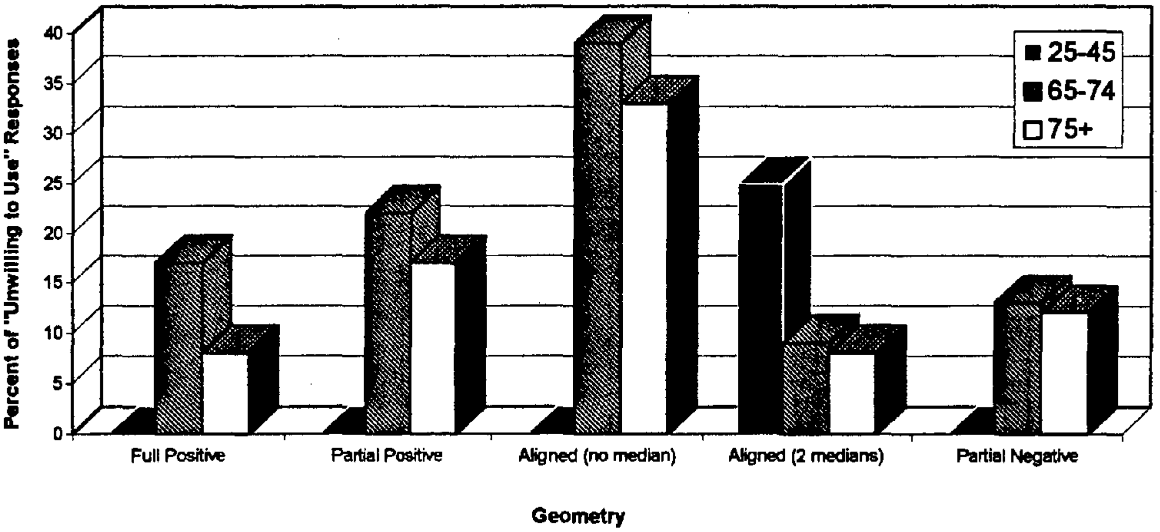
Table 43. Percentages of test subjects who indicated that they would not be willing to cross the intersection as pedestrians. [Median delineator poles were present.]

	CROSSWALK CONFIGURATION									
	Full Positive		Partial Positive		Aligned (no median)		Aligned (2 medians)		Partial Negative	
Driver Age	0.9-m/s walking speed	1.2-m/s walking speed	0.9-m/s walking speed	1.2-m/s walking speed	0.9-m/s walking speed	1.2-m/s walking speed	0.9-m/s walking speed	1.2-m/s walking speed	0.9-m/s walking speed	1.2-m/s walking speed
25-45	0	0	5	5	N/A	N/A	15	10	5	5
65-74	13	9	13	13	N/A	N/A	22	9	9	17
75+	8	21	12	12	N/A	N/A	12	12	4	12

N/A = not applicable



(a) Walking speed = 0.9 m/s (3 ft/s).



(b) Walking speed = 1.2 m/s (4 ft/s).

Figure 39. Percentages of subjects who indicated that they would not be willing to cross the intersection as pedestrians in the laboratory study, as a function of crosswalk configuration, pedestrian age, and walking speed, when there were no median delineator poles present.

Table 44. Mean safety ratings on five-point bipolar scale (1=most safe rating, 5=least safe rating) for crosswalk configurations examined in the laboratory.

[Median delineator poles were absent.]

	CROSSWALK CONFIGURATION									
	Full Positive		Partial Positive		Aligned (no median)		Aligned (2 medians)		Partial Negative	
Driver Age	0.9-m/s walking speed	1.2-m/s walking speed	0.9-m/s walking speed	1.2-m/s walking speed	0.9-m/s walking speed	1.2-m/s walking speed	0.9-m/s walking speed	1.2-m/s walking speed	0.9-m/s walking speed	1.2-m/s walking speed
25-45	2.20	2.40	2.45	2.40	4.70	2.45	3.20	3.05	1.95	2.20
65-74	2.65	2.35	2.48	2.57	3.22	3.39	2.65	2.48	2.61	2.30
75+	1.88	2.04	1.96	2.25	3.13	2.58	2.25	2.04	1.83	2.25

Table 45. Mean safety ratings on five-point bipolar scale (1=most safe rating, 5=least safe rating) for crosswalk configurations examined in the laboratory.

[Median delineator poles were present.]

	CROSSWALK CONFIGURATION									
	Full Positive		Partial Positive		Aligned (no median)		Aligned (2 medians)		Partial Negative	
Driver Age	0.9-m/s walking speed	1.2-m/s walking speed	0.9-m/s walking speed	1.2-m/s walking speed	0.9-m/s walking speed	1.2-m/s walking speed	0.9-m/s walking speed	1.2-m/s walking speed	0.9-m/s walking speed	1.2-m/s walking speed
25-45	2.15	2.40	2.00	2.45	N/A	N/A	2.75	2.55	1.95	2.00
65-74	2.22	2.26	2.39	2.22	N/A	N/A	2.04	2.09	2.04	2.00
75+	2.04	2.42	1.96	2.29	N/A	N/A	2.42	3.00	2.17	2.21

N/A = not applicable

aligned geometry with no median versus each of the three single-median crosswalk configurations (partial negative, partial positive, and full positive geometries).

The objective data are summarized in Tables 46 and 47. These results indicate the mean time elapsed after the onset of the WALK phase of the pedestrian control signal when an individual would still be willing to start across the intersection, providing a measure of the relative mobility afforded by the five crosswalk configurations studied. However, this measure was **not** obtained for any crosswalk configuration that an individual had previously indicated he/she would be unwilling to use as a pedestrian, resulting in an unbalanced design for this data analysis.

Keeping this fact in mind, inspection of Tables 46 and 47 reveals several trends. First, a clear difference between age groups is apparent, such that the 25-45 age group would always be willing to wait longer than the two older groups to begin to cross the intersection. Next, while an influence of geometry is less clear in these data than in the safety ratings, an interaction with other variables was suggested: Values obtained for this measure with the slower walking speed exceeded those with the faster walking speed for the 25-45 age group for all crosswalk configurations, for the 65-74 age group for all configurations except the one associated with partial positive geometry, and for the 75+ age group **only** for the aligned geometry configuration, **without** the presence of the median delineator poles. Figure 40 presents the mean time elapsed in seconds after the onset of the WALK phase on the (simulated) pedestrian control signal, at the last moment when subjects were still willing to begin to cross the intersection, as a function of crosswalk configuration, pedestrian age, and walking speed, when there were no median delineator poles present.

PROC GLM in SAS was used to analyze these data due to the unbalanced nature of the data set, as explained above. This analysis demonstrated a single main effect of subject age [$F(2,63)=3.64$; $p<0.0318$], without the presence of the median delineator poles. This effect was localized using a Scheffé post hoc test (alpha=0.05) to contrast between the youngest age group versus each of the two older groups. No two-way interactions were demonstrated. However, the interaction of geometry by age by simulated walking speed suggested above did reach statistical significance [$F(29,520)=1.77$; $p<0.0087$].

A discussion of the findings of the laboratory study is deferred to the end of the description of the field study of pedestrian crosswalk/median preferences.

Field Study

Independent Variables. The independent variables in the field study of pedestrian behavior in response to varying crosswalk configurations included four levels of pedestrian age (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. Pedestrian volumes were roughly 30 percent higher at the site with a median refuge island. A description of the study locations follows.

Table 46. Mean time elapsed after onset of WALK phase of pedestrian control signal when subjects were still willing to begin walking across the intersection.

[Median delineator poles were absent.]

CROSSWALK CONFIGURATION

Driver Age	Full Positive		Partial Positive		Aligned (no median)		Aligned (2 medians)		Partial Negative	
	0.9-m/s walking speed	1.2-m/s walking speed	0.9-m/s walking speed	1.2-m/s walking speed	0.9-m/s walking speed	1.2-m/s walking speed	0.9-m/s walking speed	1.2-m/s walking speed	0.9-m/s walking speed	1.2-m/s walking speed
25-45	8.77	7.37	8.20	7.66	7.98	7.93	7.36	7.31	8.07	8.25
65-74	5.55	4.90	5.66	5.83	5.01	4.33	5.07	4.67	5.51	4.47
75+	5.16	6.19	5.28	5.75	5.80	4.00	6.02	5.14	4.84	5.58

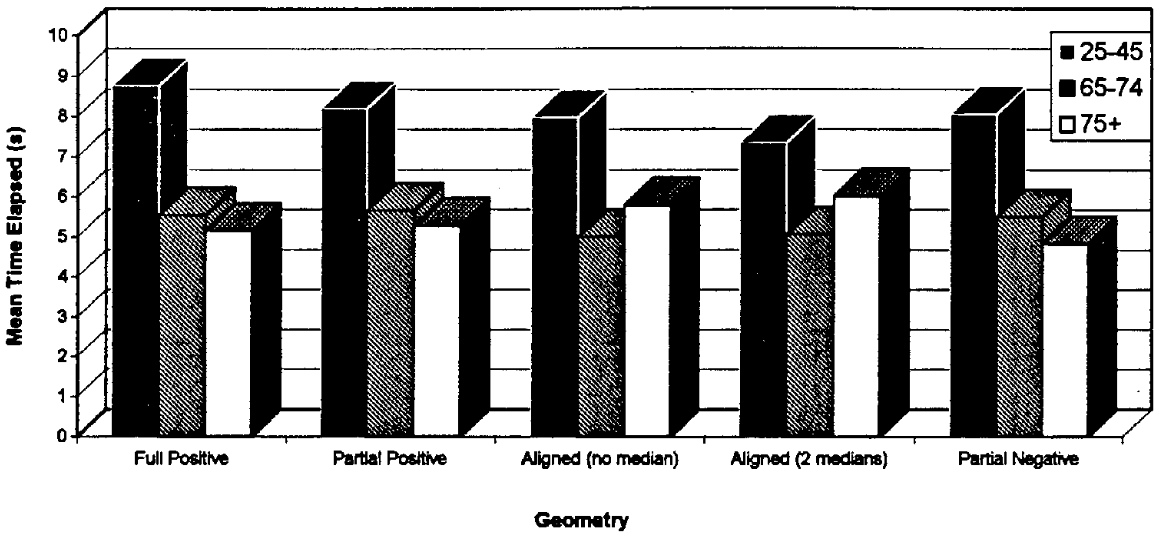
Table 47. Mean time elapsed after onset of WALK phase of pedestrian control signal when subjects were still willing to begin walking across the intersection.

[Median delineator poles were present.]

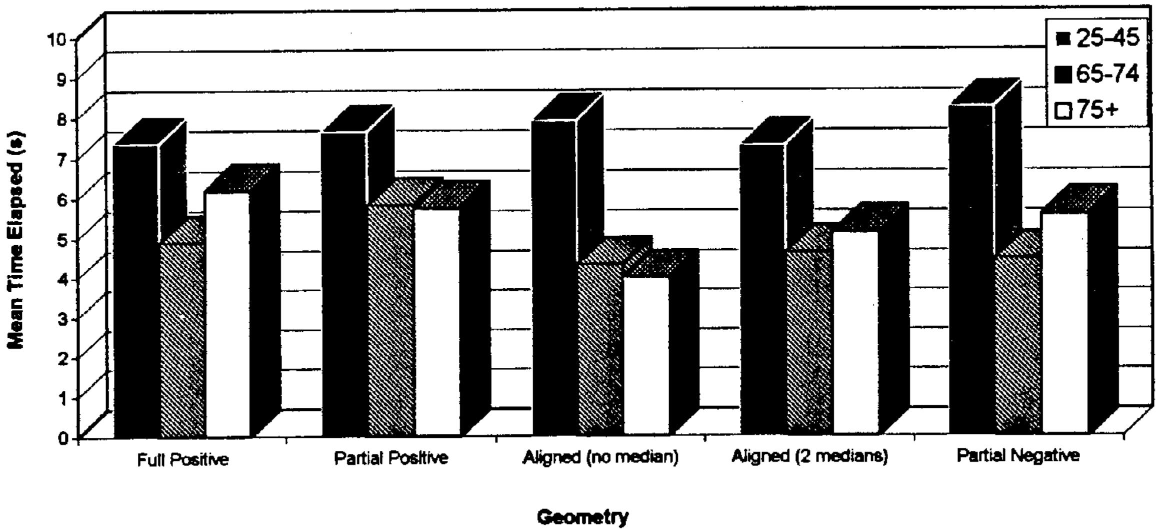
CROSSWALK CONFIGURATION

Driver Age	Full Positive		Partial Positive		Aligned (no median)		Aligned (2 medians)		Partial Negative	
	0.9-m/s walking speed	1.2-m/s walking speed	0.9-m/s walking speed	1.2-m/s walking speed	0.9-m/s walking speed	1.2-m/s walking speed	0.9-m/s walking speed	1.2-m/s walking speed	0.9-m/s walking speed	1.2-m/s walking speed
25-45	7.51	8.11	7.81	7.38	N/A	N/A	7.86	7.55	8.09	7.90
65-74	5.10	5.22	5.21	5.59	N/A	N/A	5.14	6.00	4.53	5.72
75+	4.83	5.43	5.66	5.99	N/A	N/A	6.08	5.95	4.72	5.23

N/A = not applicable



(a) Walking speed = 0.9 m/s (3 ft/s).



(b) Walking speed = 1.2 m/s (4 ft/s).

Figure 40. Mean time elapsed (in seconds) after the onset of the WALK phase of the (simulated) pedestrian control signal in the laboratory study, when subjects were still willing to begin to cross the intersection, as a function of crosswalk configuration, pedestrian age, and walking speed, when there were no median delineator poles present.

The study included two crosswalks—one with a pedestrian refuge island and the other without a refuge island (termed the "control location"). The first was a 29.6-m-long (97-ft-long) crosswalk located at the intersection of Vermont and 14th Streets in Washington, DC. It may be noted that the entry into the traffic circle (Thomas Circle) is located a short distance downstream from this intersection; however, a signal on 14th Street controlled entrance to the circle and separated the pedestrian crosswalk under study from this traffic stream. At this location, pedestrians crossed in two stages, including a wait on a properly designed refuge island located approximately in the middle of the crosswalk. Pedestrian signals provided pedestrians with the opportunity to cross to the refuge island only (signal head located on the refuge island gave pedestrians the right-of-way), then wait on the island for several seconds (because the signal head at the far end of the crosswalk indicated the steady DON'T WALK), then continue crossing to the far end of the crosswalk. In other words, waiting at the refuge island was mandatory according to the pedestrian signal plan. The 80-s pedestrian signal cycle was composed of four phases. Pedestrians waiting at one end of the crosswalk were faced with two signal heads; the "near" head was located on the refuge island, and the "far" head was located at the far end of the crosswalk. During the first phase (20 s), the near signal head displayed the steady WALK indication and the far signal head indicated the steady DON'T WALK indication. During the second phase (7 s), both signal heads (far and near) displayed the steady WALK indication. During the third phase (8 s), both signal heads (far and near) displayed the flashing DON'T WALK indication. During the fourth phase (45 s), both signal heads displayed the steady DON'T WALK indication.

The second crosswalk was a 27.7-m-long (91-ft-long) crosswalk located at the intersection of Wilson Boulevard and Stuart Streets in Arlington, Virginia. The location had no refuge island and pedestrians were required to cross in one stage. The pedestrian signal cycle was composed of three phases. During the first phase (10 s), the steady WALK indication was displayed. During the second phase (15 s), the flashing DON'T WALK indication was displayed. During the third phase (30-45 s), the steady DON'T WALK indication was displayed. This location, as explained previously, was a control site for the first location.

Dependent Variables/Measures of Effectiveness. Two types of dependent variables were measured. First, to measure the effect of a refuge island on the behavior of pedestrians of different age groups, the percentage of violators (pedestrians 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 from 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) to control for the effect of traffic volume. 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.

Test Sample. Data were obtained for a total of 436 pedestrians in 4 age groups, as shown in Table 48.

Table 48. Sample characteristics for the alternative pedestrian crosswalk configuration field study.

Pedestrian Age Group	Number of Subjects	Number of Males	Number of Females
25-45	210	119	91
46-64	109	63	46
65-74	61	32	29
75+	56	25	31

Methodology. Video data of pedestrian movements at intersections were collected between 9:00 a.m. and 2:00 p.m., including videotaping pedestrians as they crossed, as well as the pedestrian signal phases. Face-to-face interviews with the pedestrians were also conducted after they crossed. At both locations, subjects were asked two questions. The first question asked at each location was a measure of perceived ease-of-use: "Please indicate how easy it was for you to cross this intersection, using a rating scale where 1=*extremely difficult* and 7= *extremely easy.*" The second question asked at each location was a measure of pedestrian refuge island desirability, which was presented in two formats as appropriate to the specific location. At the location with the refuge island, pedestrians were asked, "Using a rating scale where 1=*extremely negative* and 7=*extremely positive*, please indicate how you would feel about the removal of the pedestrian refuge island." At the location without an island, pedestrians were asked, "Using a rating scale where 1=*extremely negative* and 7=*extremely positive*, please indicate how you would feel about the installation of a pedestrian refuge island, knowing that you would be directed by the WALK/DON'T WALK signal to cross in two stages with a stop in the middle of the crosswalk." Data were obtained for 252 pedestrians at the crosswalk containing a refuge island and for 184 pedestrians at the site without a refuge island.

Results. Table 49 shows the percentages of pedestrians who violated the pedestrian traffic light. As the last column in each cell suggests, violation of the pedestrian control signal decreased with increasing age. Pedestrians ages 65-74 and 75+ complied with the signal, however, about 40 percent of the pedestrians ages 25-45 and 46-64 did not. The last row in the table suggests that pedestrians violated the signal more often at the first location (location with the refuge island) when compared to the second location. Also, female pedestrians were less likely to violate the signal when compared to male pedestrians.

A three-factor analysis of variance (ANOVA) using the SAS GLM procedure found significant main effects of age [$F(3,3)= 178.07; p<0.0007$], gender [$F(1,3)=11.52; p<0.0247$], and location [$F(1,3)= 37.32; p<0.0088$]. None of the interactions were significant. Male pedestrians had a significantly higher violation rate than female pedestrians. Also, the location **with** the refuge island showed a higher violation rate than the location without the refuge island. A Tukey test for multiple comparisons on the age factor showed that the two younger age groups were not significantly different from each other, but were different from the two older age groups. The 65-74 and 75+ age groups were not significantly different from each other.

Table 49. Sample size (n), and frequency (f) and percentage (%) of pedestrians who violated the pedestrian crossing signal, as a function of age, gender, and location.

Pedestrian Age Group	Gender		Location		Means (All Sites)
			With Refuge Island	Without Refuge Island	
25-45	Female	n	36	42	
		f	15	11	
		%	41.7%	26.2%	34.0%
	Male	n	44	53	
		f	25	19	
		%	56.8%	35.8%	46.3%
46-64	Female	n	31	12	
		f	14	3	
		%	45.2%	25.0%	35.1%
	Male	n	42	15	
		f	20	5	
		%	47.6%	33.3%	40.4%
65-74	Female	n	14	12	
		f	0	0	
		%	0.0%	0.0%	0.0%
	Male	n	22	9	
		f	2	0	
		%	9.1%	0.0%	4.6%
75+	Female	n	20	9	
		f	0	0	
		%	0.0%	0.0%	0.0%
	Male	n	14	10	
		f	0	0	
		%	0.0%	0.0%	0.0%
Means (All Subjects)		%	25.1%	15.0%	20.1%

The results can be summarized as follows: (1) older pedestrians were significantly less likely to violate the pedestrian control signal compared to younger pedestrians; (2) female pedestrians were less likely to violate the signal than males; and (3) crosswalks with a pedestrian refuge island appeared to encourage violation of the signal compared to crosswalks without a refuge island.

With regard to the ease or difficulty of crossing, the location **with** the refuge island was rated overall as significantly **more difficult** to cross (mean rating = 3.17) than the location without the refuge island (mean rating = 4.2), as demonstrated by the SAS analysis of these subjective data [$F(1,420)=27.60; p<0.0001$]. Neither age nor gender were associated with significant differences on this measure, however.

Pedestrian responses regarding the measure of median island desirability obtained at each location were as follows: opinions concerning removal of the island where one already existed were generally negative (mean rating = 2.55), while opinions concerning the installation of an island where none presently existed were generally positive (mean rating = 4.9). The GLM procedure conducted on these data showed that location was the only significant factor [$F(1,420)=120.80; p<0.0001$], as pedestrians surveyed on this measure expressed significantly less support for removing the existing refuge island than for installing the new island.

Discussion

The field study results indicated that pedestrians perceived locations with refuge islands as being more difficult to cross than locations without refuge islands, but at the same time, pedestrians of all age/gender groups supported the idea of installing a refuge island at a crossing where none existed, and felt even more strongly that removal of an existing island was not desirable. In addition, the crosswalk with the pedestrian refuge island showed greater noncompliance behavior (pedestrians started during the DON'T WALK indications), particularly among pedestrians under age 65. The magnitude of noncompliance was 15 to 21 percent higher at the specific location where an island was present in this study. While these results are suggestive, a need remains to obtain similar measures of pedestrian response to varying intersection crosswalk configurations at a larger number of locations, before the present findings can be generalized to represent pedestrian response to intersections with vs. without refuge islands across settings.

In the laboratory, a tentative conclusion from the finding that the aligned locations had the highest "unwilling to use" responses is that a single median refuge island is preferred over either no median or two medians. This was the case even though the "no median" condition was associated with a shorter overall crosswalk length in the laboratory simulation. In the case of the two-median condition, it may tentatively be concluded that this feature added to the perceived distance and effort in traversing the intersection as a pedestrian. There was no validation of the simulation procedure (e.g., with respect to perceived distance along the crosswalk to the other curb) permitted in this project, however, so it is unknown if the perspective intersection view provided to subjects in the laboratory simulation introduced a methodological artifact into these data.

To address the question of which geometric configuration of left-turn lanes is best suited for both pedestrians and drivers, it must be reiterated that the aligned geometries as configured in the laboratory study (i.e., with no refuge island and with two refuge islands) were perceived as the most unsafe and received the highest percentages of "unwilling to use" responses by pedestrians, while there were no differences between the other offset levels (either positive or negative). In the field driving studies, the negative offsets were associated with the poorest performance, and the aligned and positive geometries were associated with the best performance. In the laboratory study with drivers, the full positive offset was distinguished from the other geometries in terms of (reduced) critical gap size, suggesting greater capacity/mobility with such designs, while the partial negative geometry demonstrated significantly poorer performance with respect to mean least-safe gap size and percent of unsafe gaps accepted. Finally, the guidelines suggested by McCoy et al. (1992) for the offset of opposite left-turn lanes are all positive. Coupled with the fact that the negatively offset and aligned conditions in the present study were associated with the longest critical gap sizes *and* shortest "least safe gap" distances for drivers, as well as the lowest safety ratings for both drivers and pedestrians, an intersection geometry providing for positively offset left-turn lanes with one pedestrian refuge island appears likely to result in the greatest overall benefit for older road users.

ALTERNATIVE RIGHT-TURN LANE GEOMETRY

This effort included seven intersections at which measures of driver performance were obtained under varying right-turn geometries. Two separate studies are described, involving data collection at four intersections and three intersections, respectively. At four of the seven intersections, the effects of channelized right-turn lanes and the presence of skew on right-turn maneuvers made by male and female drivers in three age groups were examined. At the other three intersections, the effect of varying right-turn curb radii on right-turn maneuvers made by male and female drivers in the same three age groups was studied.

Right-Turn Channelization and Skew Field Study

Independent Variables. In the study of channelization and skew for right-turn lanes, four right-turn lane geometries were examined:

(a) 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 compare to non-channelized intersections.

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

(d) A 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.

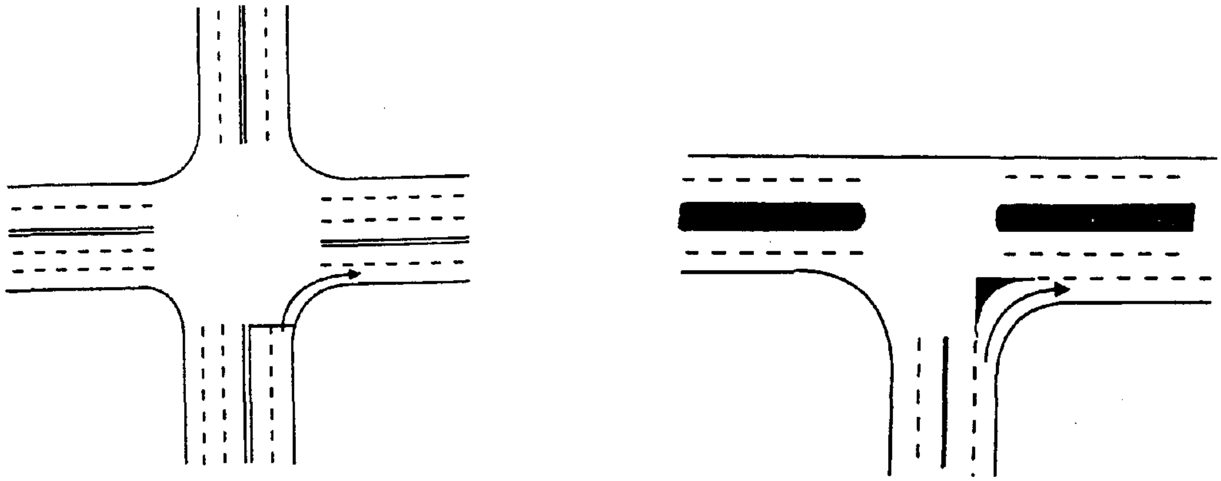
The four intersections are diagrammed in Figure 41.

Dependent Variables/Measures of Effectiveness. The measures of effectiveness for the study of right-turn channelization and skew included:

(*1*) Percentage of drivers who attempted an RTOR (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.
(*9*) General survey questions about personal responses to various traffic control devices.

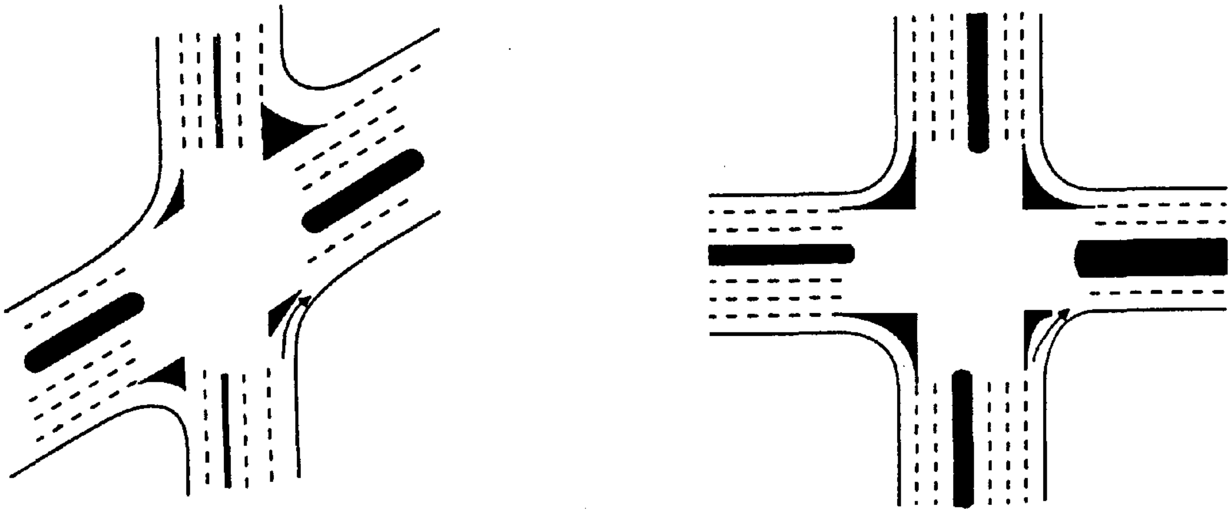
The measures of effectiveness described above as (*1*), (*2*), and (*3*) were included to examine the search patterns of drivers looking for a gap in the conflicting traffic stream. The percentage of drivers who completed an RTOR (*4*) was included as a measure of mobility at different right-turn lane configurations. The frequency of making an RTOR was defined as the percentage of subjects who made an RTOR out of the total number of subjects who had the opportunity to make an RTOR. RTOR opportunities occurred when the traffic light was red and there was no conflicting traffic approaching to prevent a subject from making an RTOR. It was hypothesized that a higher percentage of older drivers would avoid making RTOR's in comparison to younger drivers.

Next, the percentage of drivers who made an RTOR without a complete stop (*5*) was of interest, as an indicator of the relationship between right-turn lane geometry and traffic flow. This measure was defined as the percentage of the total number of RTOR opportunities in which subjects who completed this maneuver did so without stopping. It was hypothesized that younger drivers would be able to check on the conflicting traffic while approaching the intersection and make a decision to proceed or stop before reaching the merge point. In contrast, older drivers were expected to stop at the merge location, and only then try to find a merge opportunity, or simply wait to execute the maneuver during the green phase. Accordingly, this measure (*5*) was obtained even for the three channelized right-turn lanes that were controlled by yield signs. The acceleration profile after making the right turn (*6*) was examined to indicate whether older drivers' acceleration ability was different from that of the younger drivers and whether this had an effect on their mobility under different right-turn lane configurations;



(a) Non-Channelized Right-Turn Lane
at 90-Degree Intersection

(b) Channelized Right-Turn Lane
With Acceleration Lane
at 90-Degree Intersection



(c) Channelized Right-Turn Lane
Without Acceleration Lane
at Skewed Intersection

(d) Channelized Right-Turn Lane
Without Acceleration Lane
at 90-Degree Intersection

Figure 41. Intersection geometries examined in field study of right-turn lane channelization.

proficiency at this maneuver requires that a driver accelerate smoothly to merge at the speed of the conflicting traffic. The measure for free-flow speed (7) permitted a comparison of turning drivers' speed choices when not influenced by a signal or other vehicles.

Test Sample. 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. The criteria for subject selection were the same as described for the field study of alternative left-turn lanes, and some of the subjects participated in both field studies. The characteristics of the test sample are presented in Table 50.

Table 50. Characteristics of right-turn channelization and skew study test sample.

Variable	Driver Age Group					
	25-45		65-74		75+	
	Female	Male	Female	Male	Female	Male
Number of Participants	15	17	17	19	15	17
Mean Age	35.7	37.6	67.6	69.4	77.1	78.9
Mean Driving Experience (Years)	23.1	24.6	46.9	49.3	46.1	62.6
Mean No. Trips/Week	16.2	15.7	10.3	10.7	9.9	11.1
Mean No. Miles Driven/Week	134.6	213.8	87.1	161.6	115.4	176.2
Mean Automobile Power in Cylinders	5.3	4.8	5.5	5.5	5.3	6.2
Automobile Dimensions (Feet)						
Mean Lateral Wheelbase	4.8	4.7	4.9	5.0	4.8	5.0
Mean Longitudinal Wheelbase	8.5	8.6	8.9	8.9	8.8	9.0

1 ft = 0.305 m
1 mi = 1.61 km

Methodology. Two video cameras were used at each intersection to obtain the required data, and subjects were accompanied by a member of the research team who recorded certain driver performance measures. In the study of right-turn channelization, 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 within a growing urban area, 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 yield sign controlling the channelized right-turn lane with an acceleration lane was placed approximately 15.2 m (50 ft) downstream of the turn; according to the county, channelized intersections, *including those with acceleration lanes*, are controlled by yield signs for liability reasons.

The study utilized a three-factor experimental design, where the three factors were geometry, age, and gender. Each subject drove four times through the same geometric feature (i.e., four times around each test circuit), and the last three trials from each subject were included in the data set. The first trial was intended to familiarize the test subject with the test circuit. Thus, for the right-turn study, there were four locations, three age groups, and two genders, producing 24 cells (4 by 3 by 2 design). Each cell contained data points equal to the number of maneuvers made, that is, equal to the number of subjects in that cell multiplied by three (three trials per subject).

Results. Table 51 shows the percentages of the maneuvers in which drivers attempted to make an RTOR at the four study locations. As the last column in each cell suggests, only approximately 16 percent of the old-old drivers attempted to make an RTOR as compared to nearly 83 percent for drivers ages 25-45 and 45 percent for drivers ages 65-74. In all cases, female subjects chose not to attempt to make an RTOR more often than male subjects. Location did not seem to affect a driver's tendency to make an RTOR.

A three-factor analysis of variance (ANOVA) using the SAS GLM procedure found significant main effects of age [$F(2,6)=356.9; p<0.0001$] and gender [$F(1,6)=30.8; p<0.0014$]. Location did not seem to affect a driver's tendency to make an RTOR. A Tukey test for multiple comparisons of the age factor showed that the differences between all three age groups were significant. Also, male drivers had significantly higher percentages than did female drivers.

Table 52 shows the percentages of the maneuvers in which subjects depended solely on head/neck checks (direct looks) in their attempt to make an RTOR at the four study locations. Older drivers always made direct looks to check on the conflicting traffic when making an RTOR. All drivers depended exclusively on direct looks at the non-channelized location. At the skewed location, drivers tended to use side mirrors to supplement head/neck checks when looking for gaps in the conflicting traffic. The percentages of direct looks for male and female subjects were similar.

Table 51. Sample size (n), and frequency (f) and percentage (%) of drivers who attempted an RTOR, as a function of age, gender, and right-turn lane geometry.

Driver Age Group	Gender		Right-Turn Lane Geometry (See Legend Below)				Means (All Sites)
			A	B	C	D	
25-45	Female	n	19	20	20	17	
		f	15	15	14	13	
		%	78.9%	75.0%	70.0%	76.5%	75.1%
	Male	n	22	24	23	20	
		f	20	21	21	18	
		%	90.9%	87.5%	91.3%	90.0%	89.9%
65-74	Female	n	25	24	27	28	
		f	9	10	9	12	
		%	36.0%	41.7%	33.3%	42.9%	38.5%
	Male	n	22	27	26	26	
		f	13	15	10	13	
		%	59.1%	55.6%	38.5%	50.0%	50.8%
75+	Female	n	21	23	20	22	
		f	2	5	2	3	
		%	9.5%	21.7%	10.0%	13.6%	13.7%
	Male	n	23	25	22	24	
		f	5	5	3	6	
		%	21.7%	20.0%	13.6%	25.0%	20.1%
Means (All Subjects)			49.4%	50.2%	42.8%	49.7%	48.0%

A: Non-Channelized Right-Turn Lane at 90-Degree Intersection
B: Channelized Right-Turn Lane With Acceleration Lane at 90-Degree Intersection
C: Channelized Right-Turn Lane Without Acceleration Lane at Skewed Intersection
D: Channelized Right-Turn Lane Without Acceleration Lane at 90-Degree Intersection

The GLM procedure conducted on the percentages of drivers who exclusively used their head/neck (made direct looks) in their attempt to make an RTOR indicated that age [$F(2,6)=31.8$; $p<0.0006$], geometry [$F(3,6)=37.4$; $p<0.0003$], and the age-by-geometry interaction [$F(6,6)=9.8$; $p<0.0069$] were significant. The oldest subjects always did a head check when attempting an RTOR, regardless of the location, though the RTOR maneuver was extremely rare for the old-old group. A Tukey test for multiple comparisons on the age factor showed that young/middle-aged and young-old groups were not different from each other, but both were different from the old-old group. At the non-channelized intersection, all drivers used direct looks exclusively to make an RTOR. A Tukey test showed that the channelized skew location was associated with significantly fewer direct looks than the other three locations. The other three locations were not significantly different from each other. These results should be reviewed with caution because of the small sample sizes included, especially for the old-old group.

Table 52. Sample size (n), and frequency (f) and percentage (%) of drivers who depended exclusively on direct looks (head/neck only) in their attempt to make an RTOR, as a function of age, gender, and right-turn lane geometry.

Driver Age Group	Gender		Right-Turn Lane Geometry (See Legend Below)				Means (All Sites)
			A	B	C	D	
25-45	Female	n	15	15	14	13	
		f	15	14	10	12	
		(%)	100.0%	93.3%	71.4%	92.3%	89.2%
	Male	n	20	21	21	18	
		f	20	19	16	16	
		(%)	100.0%	90.5%	76.2%	88.9%	88.9%
65-74	Female	n	9	10	9	12	
		f	9	9	7	12	
		(%)	100.0%	90.0%	77.8%	100.0%	92.0%
	Male	n	13	15	10	13	
		f	13	14	7	12	
		(%)	100.0%	93.3%	70.0%	92.3%	88.9%
75+	Female	n	2	5	2	3	
		f	2	5	2	3	
		(%)	100.0%	100.0%	100.0%	100.0%	100.0%
	Male	n	5	5	3	6	
		f	5	5	3	6	
		(%)	100.0%	100.0%	100.0%	100.0%	100.0%
Means (All Subjects)			100.0%	94.5%	82.6%	95.6%	93.2%

A: Non-Channelized Right-Turn Lane at 90-Degree Intersection
B: Channelized Right-Turn Lane With Acceleration Lane at 90-Degree Intersection
C: Channelized Right-Turn Lane Without Acceleration Lane at Skewed Intersection
D: Channelized Right-Turn Lane Without Acceleration Lane at 90-Degree Intersection

Regarding the percentage of drivers who used side mirrors either exclusively or in addition to direct looks, it was initially hypothesized that some drivers might depend solely on side mirrors to check on the conflicting traffic, especially at the channelized locations. However, the results showed that the hypothesis was not true. It was found that some drivers used the side mirrors, but only as a supplementary tool to the head/neck search.

Table 53 shows the percentages of the maneuvers executed during the red phase at the four study locations, out of the total number of maneuvers that could be made on red. Young/middle-aged drivers made an RTOR nearly 80 percent of the time when they had the chance to do so, compared to nearly 36 percent for young-old and 15 percent for old-old drivers. Female drivers consistently had lower percentages than male drivers. The skewed intersection had the lowest percentages for all age-gender groups. Across all locations, drivers chose to make an RTOR approximately 45 percent of the time.

A three-factor analysis of variance using the GLM procedure found significant main effects of age [$F(2,6)=854.3; p<0.0001$], geometry [$F(3,6)=8.9; p<0.0124$], and gender [$F(1,6)=65.2; p<0.0002$], as well as a significant interaction between age and gender [$F(2,6)=6.3; p<0.0336$]. A Tukey test for multiple comparisons on the geometry factor showed that locations A, B, and D were not different from each other, but all were different from location C (skewed intersection). This result indicates that the unfavorable skew prevented an RTOR. A Tukey test on the age factor showed that the three groups were significantly different from each other. Furthermore, male percentages were significantly higher than female percentages. Note that age and gender interact with each other, indicating that the differences among age groups were not exactly consistent for both genders.

Table 54 shows the percentages of the maneuvers made on red without a complete stop at the four study locations out of the total number of maneuvers made on red. Analysis of the percentage of drivers who made an RTOR without a complete stop showed significant main effects of age [$F(2,6)=145.5; p<0.0001$], geometry [$F(3,6)=130.9; p<0.0001$], and gender [$F(1,6)=8.9; p<0.0246$], as well as a significant interaction between age and geometry [$F(6,6)=21.2; p<0.0009$]. Young/middle-aged drivers made an RTOR without a complete stop roughly 35 percent of the time, compared to nearly 25 percent for the young-old and 3 percent for the old-old drivers. Females consistently made fewer RTOR's without a complete stop than did males. The channelized right-turn lane with an exclusive acceleration lane had the largest percentage of RTOR's without a complete stop, followed by the channelized right-turn lane without an acceleration lane. The non-channelized and the skewed locations showed the lowest percentage of RTOR's without a complete stop, and were not significantly different from each other. All other location comparisons were significant. Channelized intersections with or without exclusive acceleration lanes encouraged RTOR maneuvers without a complete stop, and the three age groups also showed significantly different performance on this measure. Old-old drivers almost always stopped before making an RTOR regardless of geometry. In only 1 of 26 turns did an older driver **not stop** before making an RTOR; this occurred at the channelized right-turn lane with an acceleration lane. At the **non**-channelized intersection, 22 percent of the young/middle-aged drivers, 5 percent of the young-old drivers, and none of the old-old drivers performed an RTOR without a stop. Where an acceleration lane was available, 65 percent of the young/middle-aged drivers continued through without a complete stop, compared to 55 percent of the young-old drivers and 11 percent of the old-old drivers. Old-old females **always** stopped before an RTOR.

Table 53. Frequency (f) and percentage (%) of drivers who made an RTOR out of the total (n) who had the opportunity to make an RTOR, as a function of age, gender, and right-turn lane geometry.

Driver Age Group	Gender		Right-Turn Lane Geometry (See Legend Below)				Means (All Sites)
			A	B	C	D	
25-45	Female	n	18	18	19	17	
		f	14	13	13	12	
		%	77.8%	72.2%	68.4%	70.6%	72.2%
	Male	n	20	21	21	17	
		f	18	19	18	15	
		%	90.0%	90.5%	85.7%	88.2%	88.6%
65-74	Female	n	21	22	24	25	
		f	8	8	6	8	
		%	38.1%	36.4%	25.0%	32.0%	32.9%
	Male	n	21	25	23	22	
		f	10	12	7	10	
		%	47.6%	48.0%	30.4%	45.5%	42.9%
75+	Female	n	20	20	18	17	
		f	2	4	2	2	
		%	10.0%	20.0%	11.1%	11.8%	13.2%
	Male	n	19	22	20	21	
		f	4	4	3	4	
		%	21.1%	18.2%	15.0%	19.0%	18.3%
Means (All Subjects)			47.4%	47.6%	39.3%	44.5%	44.7%

A: Non-Channelized Right-Turn Lane at 90-Degree Intersection
B: Channelized Right-Turn Lane With Acceleration Lane at 90-Degree Intersection
C: Channelized Right-Turn Lane Without Acceleration Lane at Skewed Intersection
D: Channelized Right-Turn Lane Without Acceleration Lane at 90-Degree Intersection

Table 54. Frequency (f) and percentage (%) of drivers who made an RTOR without a complete stop, out of the total number (n) who made an RTOR, as a function of age, gender, and right-turn lane geometry.

Driver Age Group	Gender		Right-Turn Lane Geometry (See Legend Below)				Means (All Sites)
			A	B	C	D	
25-45	Female	n	14	13	13	12	
		f	3	8	1	5	
		%	21.4%	61.5%	7.7%	41.7%	33.1%
	Male	n	18	19	18	15	
		f	4	13	2	7	
		%	22.2%	68.4%	11.1%	46.7%	37.1%
65-74	Female	n	8	8	6	8	
		f	0	4	0	3	
		%	0.0%	50.0%	0.0%	37.5%	21.9%
	Male	n	10	12	7	10	
		f	1	7	0	4	
		%	10.0%	58.3%	0.0%	40.0%	27.1%
75+	Female	n	2	4	2	2	
		f	0	0	0	0	
		%	0.0%	0.0%	0.0%	0.0%	0.0%
	Male	n	4	5	3	4	
		f	0	1	0	0	
		%	0.0%	20.0%	0.0%	0.0%	5.0%
Means (All Subjects)			8.9%	43.0%	3.1%	27.7%	20.7%

A: Non-Channelized Right-Turn Lane at 90-Degree Intersection
B: Channelized Right-Turn Lane With Acceleration Lane at 90-Degree Intersection
C: Channelized Right-Turn Lane Without Acceleration Lane at Skewed Intersection
D: Channelized Right-Turn Lane Without Acceleration Lane at 90-Degree Intersection

Table 55 shows the mean time (in seconds) to accelerate 30.5 m (100 ft) at the four study locations. The GLM procedure performed on the mean time to accelerate to 30.5 m (100 ft) showed that age was the only significant variable [F(2,37)=3.72; $p<0.0337$]. Old-old drivers needed approximately 0.3 s more than young/middle-aged and young-old drivers to reach the reference point after making the right turn. The performance of the young/middle-aged and young-old drivers was not significantly different; they required approximately 5.3 s to accelerate to 30.5 m (100 ft). Translation of these data into vehicle speeds reached at the 30.5-m (100-ft) reference point is permitted by consultation of acceleration curves for a given initial speed, as per the *Policy on Geometric Design of Highways and Streets* (*Green Book*), Figure II-16 (AASHTO, 1994).

Table 55. Sample size (n), and mean (x̄) and standard deviation (s.d.) time (in seconds) to accelerate 30.5 m (100 ft), as a function of age, gender, and right-turn lane geometry.

Driver Age Group	Gender		Right-Turn Lane Geometry (See Legend Below)				All Sites
			A	B	C	D	
25-45	Female	n	16	14	14	15	59
		x̄	5.51	5.04	5.42	5.05	5.26
		s.d.	0.61	0.58	0.67	0.56	0.63
	Male	n	16	14	16	17	63
		x̄	5.39	5.39	5.39	5.09	5.31
		s.d.	0.62	0.67	0.64	0.57	0.62
65-74	Female	n	16	15	14	16	61
		x̄	5.09	5.25	5.40	5.51	5.31
		s.d.	0.54	0.56	0.78	0.56	0.65
	Male	n	18	17	18	19	72
		x̄	5.37	5.23	5.18	5.19	5.24
		s.d.	0.63	0.55	0.49	0.60	0.56
75+	Female	n	15	15	16	15	61
		x̄	5.69	5.57	5.61	5.61	5.62
		s.d.	0.55	0.71	0.66	0.69	0.64
	Male	n	16	14	14	16	60
		x̄	5.56	5.60	5.69	5.56	5.60
		s.d.	0.65	0.67	0.64	0.69	0.65
All Subjects		n	97	89	92	98	376
		x̄	5.43	5.34	5.44	5.33	5.38
		s.d.	0.62	0.64	0.65	0.64	0.63

A: Non-Channelized Right-Turn Lane at 90-Degree Intersection
B: Channelized Right-Turn Lane With Acceleration Lane at 90-Degree Intersection
C: Channelized Right-Turn Lane Without Acceleration Lane at Skewed Intersection
D: Channelized Right-Turn Lane Without Acceleration Lane at 90-Degree Intersection

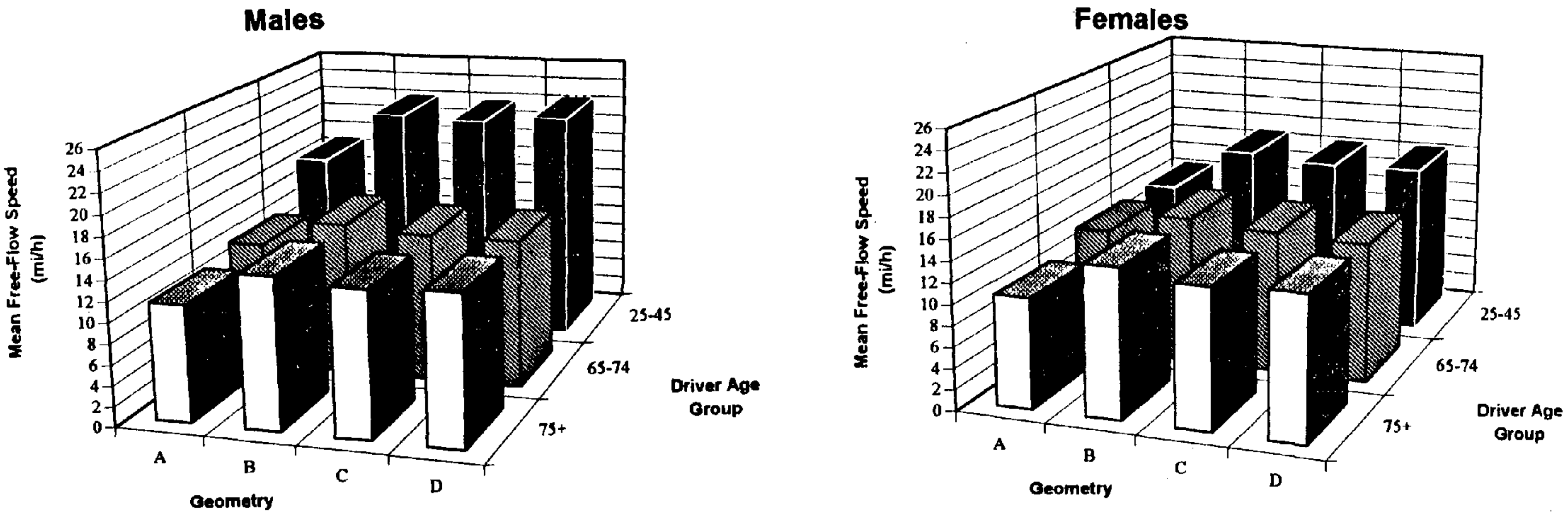
Table 56 shows the mean free-flow speeds (mi/h) at the four study locations. The GLM procedure conducted on the free-flow speeds indicated that the following main effects and interactions were significant: age [F(2,45)=139.31; $p<0.0001$]; geometry [F(3,100)=48.63; $p<0.0001$]; gender [F(1,45)=46.96; $p<0.0001$]; age by geometry [F(6,100)=4.53; $p<0.0004$]; and age by gender [F(2,32)=25.49; $p<0.0001$]. Young/middle-aged drivers made right turns at an average of 29 km/h (18 mi/h). This compares to 21 km/h (13 mi/h) for both the young-old and old-old driver groups. Young/middle-aged males had the highest speed average (33.8 km/h [21 mi/h]). Young-old and old-old females had speeds comparable to their male counterparts; however, young/middle-aged female drivers had significantly slower speeds than young/middle-aged males. The three channelized locations had comparable speeds (approximately 25.7 km/h [16 mi/h]), which were significantly faster than the speed measured at the non-channelized location (21 km/h [13 mi/h]). Figure 42 depicts mean free-flow speeds as a function of right-turn lane geometry, driver age, and driver gender.

Table 56. Sample size (n), and mean (x̄) and standard deviation (s.d.) free-flow speeds (mi/h), as a function of age, gender, and right-turn lane geometry.

Driver Age Group	Gender		Right-Turn Lane Geometry (See Legend Below)				All Sites
			A	B	C	D	
25-45	Female	n	19	17	20	20	76
		x̄	12.53	16.88	16.40	16.45	15.55
		s.d.	2.06	2.64	2.70	3.00	3.13
	Male	n	21	17	20	22	80
		x̄	16.90	22.12	21.85	22.50	20.79
		s.d.	2.74	2.74	3.80	3.45	3.94
65-74	Female	n	15	16	15	16	62
		x̄	12.20	14.25	13.73	13.44	13.42
		s.d.	1.97	2.44	2.43	2.48	2.41
	Male	n	24	20	20	22	86
		x̄	12.29	14.85	14.40	14.36	13.91
		s.d.	1.90	2.18	2.28	1.87	2.96
75+	Female	n	16	15	18	16	65
		x̄	10.50	14.20	13.33	13.69	12.92
		s.d.	1.90	1.93	2.06	2.02	2.41
	Male	n	19	17	19	19	74
		x̄	11.26	14.65	14.05	14.47	13.58
		s.d.	1.69	1.90	1.90	1.71	2.25
All Subjects		n	114	102	112	115	443
		x̄	12.75	16.18	15.77	16.08	15.16
		s.d.	2.92	3.62	3.96	4.11	3.94

1 mi/h = 1.61 km/h

A: Non-Channelized Right-Turn Lane at 90-Degree Intersection
B: Channelized Right-Turn Lane With Acceleration Lane at 90-Degree Intersection
C: Channelized Right-Turn Lane Without Acceleration Lane at Skewed Intersection
D: Channelized Right-Turn Lane Without Acceleration Lane at 90-Degree Intersection



1 mi/h = 1.61 km/h

A: Non-Channelized Right-Turn Lane at 90° Intersection
B: Channelized Right-Turn Lane With Acceleration Lane at 90° Intersection
C: Channelized Right-Turn Lane Without Acceleration Lane at Skewed Intersection
D: Channelized Right-Turn Lane Without Acceleration Lane at 90° Intersection

Figure 42. Mean free-flow speeds as a function of right-turn lane geometry, driver age, and driver gender.

Results of the specific survey and the general survey are reported next. The specific survey asked three questions to which subjects responded at each of the four study locations.

Question 1 was: "Please choose a number from 1 to 7 to indicate your level of comfort when making a right turn at this intersection, where 1= *very uncomfortable* and 7= *very comfortable*." An ANOVA found a significant main effect of geometry [F(3,149)=13.42; $p<0.0001$], as well as a significant interaction between age and geometry [F(6,149)=3.44; $p<0.0033$]. The non-channelized location was given the highest rating (5.7). The channelized lane without an acceleration lane was given the lowest rating (4.7); this difference was influenced by age, as the old-old drivers rated it as significantly more uncomfortable than the other locations.

Question 2 was: "Based on your experience making right turns at other intersections, under similar traffic conditions, the turn at this intersection was: (a) more difficult than usual; (b) easier than usual; or (c) no different—about the same as usual." The results showed that except for female subjects in the young/middle-aged group, the right turn at the channelized right-turn lanes without an acceleration lane was most often considered to be more difficult than right turns at other intersections. The right turn from the channelized right-turn lane with an acceleration lane was most often considered to be more difficult by the female subjects in the young/middle-aged group. In most age-gender groups, the right turn from the non-channelized right-turn lanes produced the lowest frequency of "more difficult" responses.

Question 3 was: "Based on your experience making a right turn on red at other intersections, under similar traffic conditions, the maneuver at this intersection was: (a) more difficult than usual; (b) easier than usual; or (c) no different—about the same as usual." Drivers' responses to this question were identical to their responses to question 2 above. This result implies that drivers felt the same way about the RTOR maneuver as they did about making the right turn in general (i.e., not necessarily on red).

The general survey asked four questions. Question 1 was: "Please consider your everyday driving experience when you need to make a right turn and the traffic light is red. Which of the following statements do you agree with the most: (a) *I am always willing to attempt to turn right on red if I feel it is safe;* (b) *I feel that it is never safe enough to turn right on red instead of waiting for the green light;* or (c) *I will attempt to turn right on red at some intersections, while at others I almost always choose to wait for the green light.*" Roughly two-thirds of the drivers are willing to attempt to make an RTOR when they feel it is safe. The other one-third is willing to attempt to make an RTOR at selected intersections. Fisher's Exact Test did not reveal any significant association between age or gender, and drivers' responses to this question.

Question 2 in the general survey was: "If you attempt to make a right turn on red—assuming everything is clear with crossing traffic—which of the following statements would best describe your reaction to pedestrians wishing to enter the crosswalk that's just in front of your car: (a) *I usually wait for all pedestrians crossing from either direction to pass in front of me before making the right turn;* (b) *I usually make the turn before any pedestrians actually begin to cross ahead of me;* or (c) *I usually wait for pedestrians leaving from the near right corner to cross, but then make the turn ahead of any pedestrians crossing from the opposite* *direction.*" About 40 percent of the young/middle-aged drivers would make an RTOR before pedestrians cross from the far side, compared to nearly 15 percent of the young-old and old-old drivers. Overall, three-quarters of the drivers would wait for all pedestrians before they make an RTOR. Fisher's Exact Test did not reveal any significant association between age or gender, and drivers' responses to this question, except that female drivers from different age groups responded differently ($p = 0.027$). Young/middle-aged drivers, especially females, were more likely than young-old and old-old drivers to only wait for pedestrians from the near right corner.

Question 3 in the general survey was: "Of the following maneuvers at an intersection, which is the most stressful for you: (a) making a left turn on a green ball; (b) making a left turn on a green arrow; or (c) making a right turn on red." The vast majority of drivers (86 percent) believed that making a left turn on a green ball (unprotected left turn) was the most stressful maneuver at the intersection. A Fisher's Exact Test did not reveal any significant association between age or gender, and drivers' responses to this question.

Question 4 in the general survey was: "Which of the following statements best describes your usual reaction when you are approaching an intersection and the light turns yellow: (a) *I usually continue on through the intersection;* or (b) *I usually stop at the intersection.*" Results showed that just over half of the young/middle-aged subjects (56 percent) indicated that they tend to continue through the intersection, while the majority of the young-old subjects (74 percent) and old-old subjects (84 percent) indicated that they usually stopped. Although there was no significant interaction between age or gender and subjects' responses to this question, female subjects from different age groups responded differently. Young females were somewhat less likely to stop for a yellow light than older females.

Right-Turn Curb Radius Field Study

Independent Variables. In the study of curb radius alternatives, three intersections provided right-turn curb radii as follows:

(a) Large curb radius of 12.2 m (40 ft).

(b) Medium curb radius of 7.6 m (25 ft).

(c) Small curb radius of 4.6 m (15 ft).

Dependent Variables/Measures of Effectiveness. 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.

Figure 43 depicts the vehicle positions defined by entrance distance, center distance, and exit distance in the right-turn curb radius study.

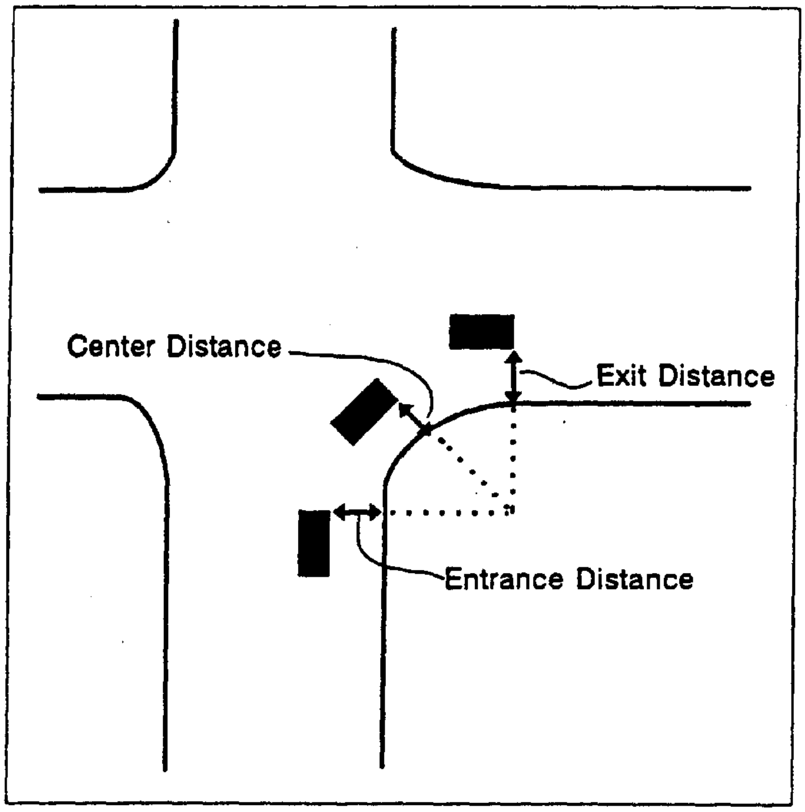


Figure 43. Vehicle positions defined by entrance distance, center distance, and exit distance in the right-turn curb radius study.

Test Sample. The participants who completed the field study of right-turn curb radius were the same subjects who participated in the study of right-turn lane channelization and skew, described previously.

Methodology. Each test subject, accompanied by one member of the research team, drove around three test circuits using the local street network in Arlington, VA. Subjects operated their own vehicles and drove through each circuit four times, resulting in four right-turn maneuvers at each study location. The order in which test subjects drove around the three test circuits was counterbalanced to reduce order effects. Although each subject drove four times through the same geometric feature, only the last three trials were included in the data set for each subject. The first trial was intended to familiarize the subject with the test circuit. The experimental design was a 3 by 3 by 2 design (three locations, three age groups, and two genders); each cell included data points equal to the number of subjects in that cell multiplied by three (three trials per subject).

Temporary lines were marked on the pavement at the entrance, center, and exit of the circular curve of the right-turn corner. The lines were marked by numbers every 0.3 m (1 ft). On a tape recorder, one observer verbally recorded the number at which the front-right wheel crossed each line. A video camera was located at the corner of the intersection and was focused on the right-turn lane at the intersection corner. The camera was focused on a temporary line marked on the pavement at the center of the corner. By superimposing the time to the nearest 1/100 s on the recorded video signal, it was possible to precisely record the instant at which the front-right and rear-right wheels crossed the reference line. The difference between the two times was the time required by the vehicle to travel a distance equal to its wheel base. Since the wheel base distances were measured on all test vehicles, it was possible to calculate the speeds of the test vehicles.

Results. The mean entrance distances at the three study locations were 1.32 m (4.32 ft) at the 12.2-m (40-ft) curb radius location, 0.78 m (2.56 ft) at the 7.6-m (25-ft) curb radius location, and 0.76 m (2.48 ft) at the 4.6-m (15-ft) curb radius location. A three-factor analysis of variance (ANOVA) using the SAS GLM procedure indicated that location was the only significant factor in the model [$F(2,80)=109.64; p<0.0001$]. There were no significant differences in performance as a function of driver age or gender. A Tukey test for multiple comparisons on the location factor showed that performance at the 12.2-m (40-ft) curb radius location was significantly different from performance at the 7.6- and 4.6-m (25- and 15-ft) curb radii locations. Performance at the 7.6- and 4.6-m (25- and 15-ft) curb radius locations was not significantly different. This result indicates that drivers enter a curve with a large radius at a distance farther away from the pavement edge compared to locations with smaller curb radii.

The mean center distances showed the same pattern as described above for entrance distances. The mean center distance values were comparable to each other at the 7.6-m and 4.6-m (25-ft and 15-ft) locations [0.92 m (3.03 ft) and 0.87 m (2.86 ft), respectively], which were lower than at the 12.2-m (40-ft) location [1.44 m (4.73 ft)]. Age and gender did not appear to affect the mean center distance. A three-factor ANOVA using the GLM procedure showed that location was the only significant factor in the model [$F(2,80)=134.30; p<0.0001$]. A Tukey test for multiple comparisons on the location factor showed that the 12.2-m (40-ft) curb radius location was significantly different from the other two locations, which were not significantly different from each other. This result indicates that drivers took wider turns at the center of the right-turn corner at the 12.2-m (40-ft) radius curve than at the 7.6- and 4.6-m (25- and 15-ft) radius curves.

The mean exit distance values were 1.52 m (4.99 ft) at 12.2-m (40-ft) radius curve, 1.1 m (3.60 ft) at the 7.6-m (25-ft) radius curve, and 1.36 m (4.47 ft) at the 4.6-m (15-ft) radius curve. A three-factor ANOVA using the GLM procedure found that location was the only significant factor in the model [$F(2,80)=112.83; p<0.0001$]. A Tukey test for multiple comparisons on the location factor showed that performance at all three locations was significantly different. This result indicates that drivers took a wider exit path at the 12.2- and 4.6-m (40- and 15-ft) radii curves than at the 7.6-m (25-ft) radius curve.

Table 57 shows the mean free-flow speed at the center of the corner at the three study locations. A three-factor ANOVA using the GLM procedure found that all main effects and their interactions were significant as follows: age [$F(2,50)=54.17; p<0.0001$], gender [$F(1,43)=11.27; p<0.0017$], geometry [$F(2,80)=80.19; p<0.0001$], age by gender [$F(2,43)=7.13; p<0.0021$], age by geometry [$F(4,80)=10.72; p<0.0001$], and age by gender by geometry [$F(4,61)=3.14; p<0.0207$]. Speed increased with increases in curb radius, and decreased as driver age increased. Males generally displayed faster speeds than females. Because of the multiple interactions, general trends in the three factors were not apparent. However, the data itself suggest the following: (1) the fastest speeds were produced by the young/middle-aged group at the 12.2-m (40-ft) curb radius location, particularly by male subjects; (2) the slowest speeds were shown for older drivers at the 4.6-m (15-ft) radius location, particularly so for the oldest females; (3) young/middle-aged drivers showed the least variability in speed as a function of geometry (with the exception of young/middle-aged males at the 12.2-m [40-ft] radius location) and old-old drivers showed the greatest variability as a function of curb radius; and (4) the largest gender differences were shown for the young/middle-aged group at the 12.2-m (40-ft) location and for the old-old group at the 4.6-m (15-ft) location. By comparison, the speeds of the young-old males and females were nearly identical to each other at each of the three locations. Figure 44 depicts the mean free-flow speeds as a function of right-turn curb radius, driver age, and driver gender.

Discussion

The results of the right-turn channelization and skew study 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 non-channelized 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.

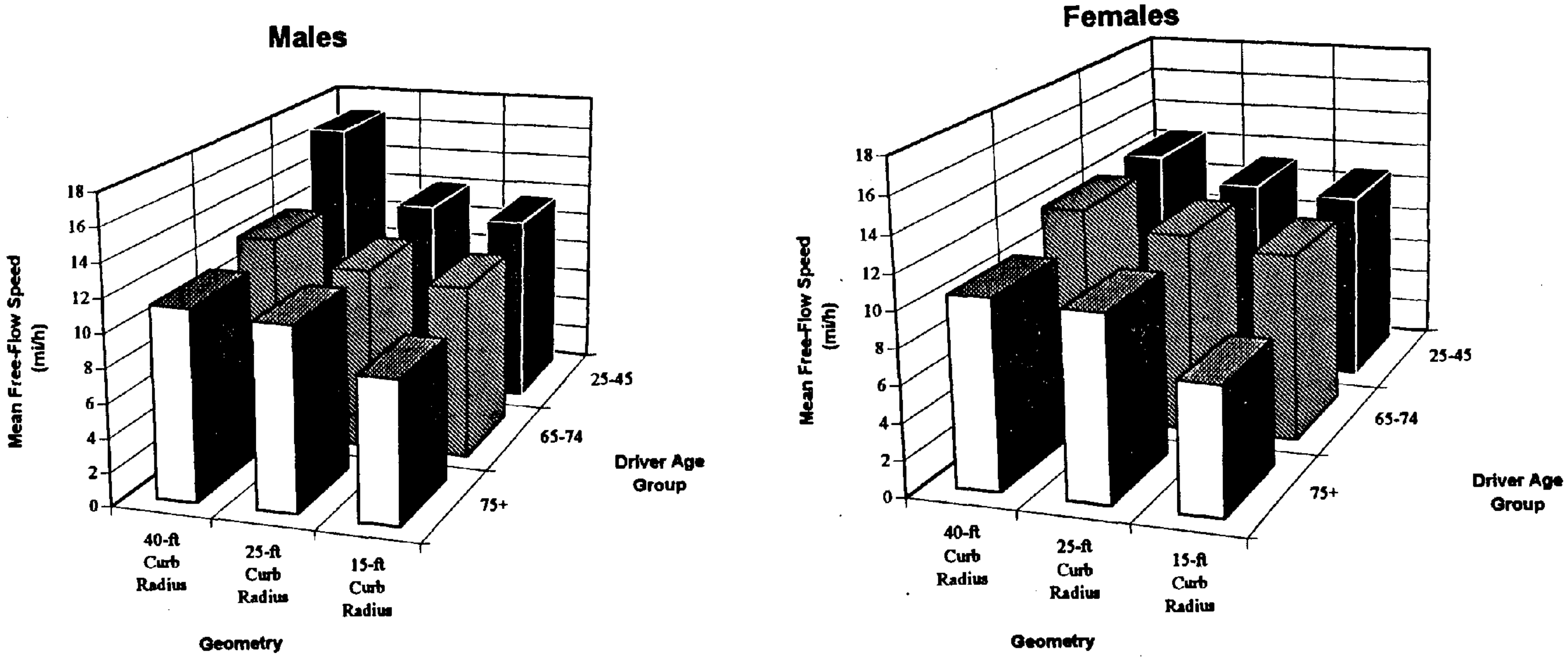
Driver perceptions of the level of comfort and degree of difficulty were influenced by age as well as right-turn lane geometry. Young/middle-aged and old-old drivers were most comfortable in making right turns on approaches with non-channelized right-turn lanes, whereas young-old drivers were most comfortable in making right turns on approaches with channelized right-turn lanes with acceleration lanes on the cross street. In general, 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. Non-channelized right-turn lanes were perceived as being less difficult than right turns at other locations.

Table 57. Sample size (n), and mean ($\bar{x}$) and standard deviation (s.d.) free-flow speeds (mi/h) as a function of age, gender, and right-turn curb radius.

Driver Age Group	Gender		Right-Turn Curb Radius			All Sites
			12.2 m (40 ft)	7.6 m (25 ft)	4.6 m (15 ft)	
25-45	Female	n	19	32	39	90
		$\bar{x}$	12.53	11.19	10.82	11.31
		s.d.	2.06	1.64	1.70	1.86
	Male	n	21	36	43	100
		$\bar{x}$	16.90	12.11	11.49	12.85
		s.d.	2.74	1.77	1.37	2.81
65-74	Female	n	15	33	39	87
		$\bar{x}$	12.20	11.21	10.54	11.08
		s.d.	1.97	1.54	1.29	1.62
	Male	n	24	40	41	105
		$\bar{x}$	12.29	10.85	10.29	10.96
		s.d.	1.90	1.27	1.40	1.66
75+	Female	n	16	28	34	78
		$\bar{x}$	10.50	10.21	6.97	8.86
		s.d.	1.90	1.52	1.31	2.25
	Male	n	19	31	36	86
		$\bar{x}$	11.26	10.84	8.36	9.90
		s.d.	1.69	1.21	1.40	1.92
All Subjects		n	114	200	232	546
		$\bar{x}$	12.54	11.10	9.86	10.92
		s.d.	2.92	1.59	2.08	2.39

1 mi = 1.61 km/h

The results of the right-turn curb radius study indicated that center distances were independent of driver age and gender, but dependent on the curb radius. Also, 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 0.61 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.



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

Figure 44. Mean free-flow speeds as a function of right-turn curb radius, driver age, and driver gender.

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.

The results of the analysis of the responses to the general survey questions indicated that the driver age-gender groups tended to have similar views with respect to the safety and practice of making right turns on red and responding to the yellow signal indication. The significant differences found on these measures indicate that male drivers are less cautious about making a right turn on red and are less likely to stop for a yellow signal indication than females.

SIGHT DISTANCE DESIGN REVIEW AND EXPERT PANEL MEETING

SIGHT DISTANCE DESIGN REVIEW

Objective

The objective of the sight distance design review was to identify the critical parameters in determining available, required, and desirable sight distance for left-turning drivers, and to present the applicable models for calculation of design values to an expert panel assembled to review the findings-to-date in this research. Both physical and behavioral measures are taken into account, using data obtained from the four left-turn lane offsets (-4.3 m, -0.91 m, 0 m, and +1.8 m [-14 ft, -3 ft, 0 ft, and +6 ft]) evaluated in the field study. These offset levels cover the range of left-turn lane offsets at a majority of intersections. The expert panel's consideration and discussion of the results of this work led to recommendations for the later development of guidelines for opposite left-turn lane geometry to accommodate older road users.

Critical Variables and Their Interrelationships

A sight distance problem occurs when the sight distance available to drivers making left turns is less than the sight distance required to turn left safely. The available sight distance depends on the degree to which the driver's line of sight is obstructed by opposite left-turning vehicles and the extent to which it is limited by the alignment of the roadway. The degree of obstruction caused by an opposite left-turning vehicle is determined by its size and position in the field of view. Where drivers of opposite left-turning vehicles position their vehicles with respect to one another in the intersection determines the extent to which they restrict each other's line of sight. Often they position themselves in the intersection in a way that minimizes the amount of sight distance obstruction they cause each other and reduces the distance required to complete their turns. In this way, they attempt to overcome the sight distance problems created by the placement of opposite left-turn lanes at many intersections. A knowledge of this behavior is essential to the development of meaningful guidelines for offsetting opposite left-turn lanes. The only known study that examined this behavior was that conducted in Nebraska by McCoy, Navarro, and Witt (1992). In their study, McCoy et al. examined the positioning behavior of left-turn vehicles turning from 3.7-m (12-ft) left-turn lanes in 4.9-m (16-ft) curbed medians with 1.2-m (4-ft) medial separators. In other words, they studied the positioning behavior where the offset between opposite left-turn lanes was negative 1.2m (4 ft). The positioning behavior at this particular site, however, may not generalize to other left-turn lane offset levels. It should also be noted that the horizontal and vertical curvature on the approaches are key geometric design elements that determine how much sight distance is available to a left-turning driver. Current models typically assume tangent, 90° approaches.

The required sight distance is the length of roadway ahead needed to see opposing through traffic that is too close to enable safe left turns. Thus, the time needed to turn left and the speed of the opposing traffic determine the required sight distance. The method presently used by practitioners to compute the required sight distance for the turn maneuver is based on the formula for a crossing maneuver presented in the AASHTO (1994) design guide, i.e.,

$SD = 1.47\ V\ (J + t_a)$.[1] This review indicated that the value used for t_a (the time required to cross the roadway) may be inappropriate for older drivers, however. In the AASHTO model, t_a is read directly from AASHTO Figure IX-33, which presents acceleration time in seconds as a function of distance traveled during acceleration for three design vehicles. The maneuver times observed in the field study in this project provide an alternative estimator for this parameter value.

Positioning Behavior. Vehicle positioning refers to the location within an intersection at which a left-turning vehicle waits for an acceptable gap in the opposing through-traffic stream. The vehicle positioning of the left-turning vehicles is defined by their longitudinal and lateral position in the intersection. The longitudinal position is the longitudinal distance of the vehicle's front-left corner from the extension of the nearest lane into which it could turn on the cross street; the lateral position is the lateral distance of the vehicle's front-left corner from the extension of the left edge of the lane from which it is turning.

The lateral and longitudinal positions of the vehicles in the field study that positioned themselves in the intersection are shown in Tables 58 and 59. The lateral positions of the vehicles that did not position themselves in the intersection, i.e., stopped behind the stop bar, are shown in Table 60. The positioning values represent the positioning behavior of drivers attempting to make a left turn through the conflicting through traffic while being opposed or blocked by at least one vehicle trying to make a left-turn maneuver from the opposite direction. As expected, the lateral positions of the positioned vehicles are always less than the lateral positions of the unpositioned vehicles. An ANOVA using the SAS GLM procedure conducted on the positioning data did not reveal any significant differences between driver age groups or genders for this behavior. While noting that this research has documented a greater tendency for older drivers and females to remain at the stop bar when attempting to turn left, of those drivers who *do* position themselves within the intersection, individuals of different age-gender groups positioned their vehicles in the same manner while waiting to make the turn. This finding suggests that *available* sight distances at locations with varying geometry may be calculated without regard to driver gender or age.

Maneuver-Time Behavior. Maneuver time is the time needed by a left-turning vehicle to complete the left-turn maneuver and clear the path of the conflicting through traffic. Together with the speed of the conflicting through traffic, maneuver time determines the sight distance required to safely complete the left-turn maneuver. Field study maneuver times (clearance times) for unpositioned and positioned vehicles were reported earlier, in Tables 37 and 38, respectively. As expected, maneuver times of unpositioned vehicles were greater than those of positioned vehicles, since unpositioned vehicles must travel longer distances to complete the maneuver, but the SAS GLM procedure conducted on the maneuver-time data did not reveal any significant differences between different age groups or genders. In other words, drivers of different age-gender groups needed the same time—within narrow limits—to complete the left turn. This finding, while counterintuitive, suggests that *required* sight distance at locations with varying geometry may also be calculated without regard to driver gender or age. This issue will be revisited in the following chapter, however.

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[1] AASHTO. (1994). *A Policy on Geometric Design of Highways and Streets*. Washington, DC.

Table 58. Sample size (n), and mean ($\bar{x}$) and standard deviation (s.d.) lateral position (in feet) for positioned vehicles, as a function of age, gender, and opposite left-turn lane offset.

Driver Age Group	Gender		Opposite Left-Turn Lane Offset				All Sites
			-14 ft	-3 ft	Aligned (0 ft)	+6 ft	
25-45	Female	n	22	23	24	20	89
		$\bar{x}$	-4.7	0.3	1.0	0.9	-0.6
		s.d.	1.3	1.1	0.7	0.6	2.5
	Male	n	21	23	25	21	90
		$\bar{x}$	-5.0	0.0	0.9	0.9	-0.7
		s.d.	1.6	1.1	0.9	0.6	2.6
65-74	Female	n	21	23	20	21	85
		$\bar{x}$	-4.6	0.1	0.8	1.0	-0.7
		s.d.	1.2	1.0	0.9	0.8	2.5
	Male	n	23	28	22	26	99
		$\bar{x}$	-4.8	-0.2	0.8	0.8	-0.8
		s.d.	1.4	0.8	0.7	0.7	2.5
75+	Female	n	19	15	15	17	66
		$\bar{x}$	-4.9	0.2	0.7	0.9	-1.0
		s.d.	1.4	1.0	0.8	0.6	2.7
	Male	n	17	15	15	16	63
		$\bar{x}$	-4.9	0.5	0.6	1.0	-0.8
		s.d.	1.4	1.0	0.7	0.6	2.7
All Subjects		n	123	127	121	121	492
		$\bar{x}$	-4.8	0.1	0.8	0.9	-0.8
		s.d.	1.4	1.0	0.8	0.7	2.6

1 ft = 0.305 m

Table 59. Sample size (n), and mean ($\bar{x}$) and standard deviation (s.d.) longitudinal position (in feet) for positioned vehicles, as a function of age, gender, and opposite left-turn lane offset.

Driver Age Group	Gender		Opposite Left-Turn Lane Offset				All Sites
			-14 ft	-3 ft	Aligned (0 ft)	+6 ft	
25-45	Female	n	22	23	24	20	89
		$\bar{x}$	19.9	24.0	24.3	26.4	23.6
		s.d.	7.5	7.5	5.8	6.6	7.1
	Male	n	21	23	25	21	90
		$\bar{x}$	19.3	23.2	23.4	27.0	23.2
		s.d.	6.4	7.1	5.7	6.7	6.9
65-74	Female	n	21	23	20	21	85
		$\bar{x}$	19.6	24.9	22.8	26.1	23.4
		s.d.	6.0	6.7	5.9	6.9	6.8
	Male	n	23	28	22	26	99
		$\bar{x}$	20.0	22.6	23.5	26.2	23.2
		s.d.	5.0	7.3	5.1	6.0	6.3
75+	Female	n	19	15	15	17	66
		$\bar{x}$	19.0	24.6	23.7	26.6	23.3
		s.d.	5.0	6.3	6.4	6.0	6.5
	Male	n	17	15	15	16	63
		$\bar{x}$	19.9	23.1	23.1	26.8	23.2
		s.d.	5.8	7.8	6.5	6.6	7.0
All Subjects		n	123	127	121	121	492
		$\bar{x}$	19.6	23.7	23.5	26.5	23.3
		s.d.	5.9	7.1	5.8	6.4	6.7

1 ft = 0.305 m

Table 60. Sample size (n), and mean ($\bar{x}$) and standard deviation (s.d.) lateral position (in feet) for unpositioned vehicles, as a function of age, gender, and opposite left-turn lane offset.

Driver Age Group	Gender		Opposite Left-Turn Lane Offset				All Sites
			-14 ft	-3 ft	Aligned (0 ft)	+6 ft	
25-45	Female	n	2	3	4	2	11
		$\bar{x}$	1.5	1.7	3.0	2.5	2.3
		s.d.	0.7	0.6	0.0	0.7	0.8
	Male	n	1	1	1	0	3
		$\bar{x}$	1.0	2.0	4.0	—	2.3
		s.d.	—	—	—	—	1.5
65-74	Female	n	5	5	4	4	18
		$\bar{x}$	1.8	3.0	2.5	3.0	2.6
		s.d.	0.4	0.7	1.7	0.8	1.0
	Male	n	5	4	4	4	17
		$\bar{x}$	2.2	3.2	1.8	3.0	2.5
		s.d.	0.8	0.5	1.5	0.8	1.1
75+	Female	n	7	7	9	10	33
		$\bar{x}$	2.0	2.3	2.7	2.9	2.5
		s.d.	0.6	1.4	1.3	0.7	1.1
	Male	n	5	8	8	6	27
		$\bar{x}$	1.8	2.4	3.0	3.2	2.6
		s.d.	0.8	1.3	1.1	0.8	1.1
All Subjects		n	25	28	30	26	109
		$\bar{x}$	1.9	2.5	2.7	3.0	2.5
		s.d.	0.7	1.1	1.2	0.7	1.4

1 ft = 0.305 m

Percent of Driving Population Accommodated by Geometric Design. As mentioned earlier, the available sight distance to a left-turning vehicle is a function of both its position within the intersection and the position of the opposite left-turning vehicle within the intersection. In this research, it is assumed that guidelines should be developed that use the 95th percentile positioning values of the left-turning *and* opposite left-turning vehicles. Thus, if the locations of the left-turning and opposite left-turning vehicles are **independent**, the guidelines would be expected to accommodate about 90 percent of all left-turning vehicles (both directions). This approach takes into account the behavior of all but the slowest 5 percent of the older driving population.

The key vehicle-positioning measures for guideline development, as obtained in the earlier field study in this project, are displayed in Table 61. 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 61. Vehicle positioning and maneuver-time design values used to develop guidelines.

Value Description	Value Level at Left-Turn Lane Offsets of			
	-14 ft	-3 ft	0 ft	+6 ft
5th Percentile Longitudinal Position of Opposed, Positioned Left-Turn Vehicles (feet)	10.4	9.3	14.0	16.3
95th Percentile Lateral Position of Opposed, Positioned Left-Turn Vehicles (feet)	-3.2	1.5	1.8	1.7
95th Percentile Lateral Position of Opposed, Unpositioned Left-Turn Vehicles (feet)	2.7	3.8	3.8	3.8
95th Percentile Maneuver Time of Opposed, Positioned Left-Turn Vehicles (seconds)	3.8	3.9	3.9	3.9
95th Percentile Maneuver Time of Opposed, Unpositioned Left-Turn Vehicles (seconds)	6.7	6.4	6.6	5.7

1 ft = 0.305 m

The guidelines subsequently developed for left-turn lane offset are based on a comparison between the available and required sight distances at a given site. The minimum offsets between opposite left-turn lanes were determined by setting the expression derived for available sight distance equal to the required sight distance and solving for the offsets needed to provide the required sight distances. Furthermore, sight distance requirements were derived according to both the existing AASHTO formula, referenced earlier, and as prescribed by variations on a gap acceptance model as investigated in NCHRP Project 15-14(1) by Harwood et al. (in press).

This work follows the description of the Expert Panel meeting.

OLDER ROAD USERS EXPERT PANEL MEETING

Panel Objectives and Organization

A concluding task in this project was a second meeting of the Older Road User Expert Panel. The panel was reconvened for a 1½-day meeting in the Arlington, VA office of The Scientex Corporation to review the findings of the laboratory and field investigations, ultimately leading to the development of recommendations for improved intersection geometric design and operations to aid older road users. A further objective of the panel was to generate and consider as a group a set of project ideas for future research in this area.

The panel members are listed in Table 62, and include practicing traffic engineers, traffic engineers primarily involved in research, and a research psychologist. As a group, the panelists represent membership in or affiliation with the following professional organizations: TRB Committee on Geometric Design (A2A02); TRB Committee on Operational Effects of Geometrics (A3A08); TRB Committee on Visibility (A3A04); Illuminating Engineering Society (IES); Institute of Transportation Engineers (ITE); American Society of Civil Engineers (ASCE); Operations Research Society of America (ORSA); ITS America; Society of Automotive Engineers (SAE); and the Human Factors and Ergonomics Society (HFES). FHWA staff and their representatives attending the panel meeting included: Elizabeth Alicandri (FHWA), and Essie Kloeppel, Robert Peters, and Mark Robinson (SAIC).

Table 62. Older Road User Expert Panel convened to review project findings and develop recommendations.

Name	Organization	Expertise
Stanley Byington	Consultant (retired Scientex/FHWA)	Traffic Engineer
Mark Freedman	Westat, Inc	Traffic Engineer
Miguel Gavino	Washington State DOT	Traffic Engineer
Donald Gilbertson	Wisconsin State DOT	Traffic Engineer
David Harkey	UNC/HSRC	Traffic Engineer
Neil Lerner	COMSIS Corporation	Psychologist
Patrick McCoy	University of Nebraska-Lincoln	Traffic Engineer
Timothy Neuman	CH2M Hill	Traffic Engineer
Richard Skopik	Texas Department of Highways	Traffic Engineer
Mohammed Tarawneh	Consultant (previously with Scientex)	Traffic Engineer

The Scientex staff leading and contributing to the panel discussion were Loren Staplin and Kathy Lococo. Moe Tarawneh, a project consultant, led the discussion addressing the field studies and sight distance analysis.

Panel Procedures and Results

The panel was presented with a description of laboratory and field data collection methods, study findings, and preliminary recommendations in an Executive Summary document prior to meeting in Arlington, VA. This information was reviewed at the panel meeting. Panel members then were presented with the sight distance design review.

Following these presentations, the panel's attention was focused on the extent to which the evidence obtained in these efforts is sufficient to support recommendations for specific elements of intersection geometric design and operational improvements. Generally speaking, a consensus emerged that the development of guidelines regarding the design of opposite left-turn lane geometry to meet sight distance requirements for turning drivers was appropriate in light of present findings, but that specific recommendations pertaining to pedestrian crosswalk elements and right-turn channelization would be premature. Instead, it was the collective judgment of the assembled experts that identifying future research needs to fill gaps in knowledge in these areas was the most useful outcome of the pedestrian crosswalk and right-turn channelization data collected in this project.

Consequently, a subsequent effort to develop design guidelines for the geometry of left-turn lanes at intersections was undertaken. This topic is addressed in the following section of the final report, according to panel recommendations voiced during discussion in this meeting of competing models and formulas for computing sight distance requirements. Specifically, it was deemed most useful to perform additional analyses to reveal how calculations as presently prescribed by the *Green Book* versus those which follow from application of a gap acceptance model, with varying assumptions regarding driver behavioral response in the left-turn situation, lead to different intersection design guidelines.

The development of guidelines for changes in traffic operations and traffic control device practices that complement design recommendations or may be warranted where design recommendations are not feasible to be implemented in a particular location was also supported by the panel. These follow in the next section.

Finally, with regard to future research needs, the panel members were asked to make recommendations addressing specific geometric design and/or operational elements of intersections that they believed could benefit older drivers and/or pedestrians, and to include candidate variables and proposed methodologies. In an open discussion, which included lengthy and vigorous debate of the merits of each idea presented to the group, the panel ultimately agreed upon 15 research recommendations, some of which represented a consolidation of previously separate ideas into a common statement of research needs. Using private ballots, the panel members—excluding FHWA representatives and Scientex staff present—then individually rank-ordered the list of research needs, with a ranking of 1 indicating the highest priority and a ranking of 15 indicating the lowest priority. Mean ranking scores were calculated to yield a final set of panel recommendations for further research. These recommendations are presented in Table 63.

Table 63. Expert Panel recommendations for future research on intersection geometric design, operations, and traffic control devices.

Rank	**Statement of Research Need**	**Mean Ranking**
1	Analyze left-turn accident types as a function of specific geometric and operational characteristics. Use a case-control study (matched intersections with stable operations) and compare offset dimensions. Normalize accident rates by exposure measurements. Conduct a cost-benefit analysis of geometric "enhancements" (e.g., sight distance). Classify accidents according to their potential relationships to geometric design/operational variables (what kinds of accidents are increased or decreased by level of offset?). Conduct a taxonomy of crashes to determine which are related to offset level (sight distance) and which are unrelated, then perform a relevant crash risk analysis as it relates to offset.	4.1
2	Study the interrelationships of crosswalk elements on pedestrian behavior (e.g., number of medians, median width, crossing length, lighting, signalization and timing, traffic volume and turning movements, crosswalk delineation, type of environment—urban, suburban, rural) to allow the development of guidelines to accommodate diminished-capacity pedestrians. Perform lab and/or observational field studies. Include task demand measures (e.g., visual search, attention) to quantify task demands of intersections. Control for familiarity level as this affects the task demand. Expand the laboratory study to incorporate median signals, and vary pedestrian messages. Consider the use of a virtual environment to study how pedestrians decide to control movements, and include variations in pedestrian signal characteristics and traffic speeds.	5.3
3	Include unobtrusive behavioral observations in actual traffic to complement study MOE's in future studies of driver and pedestrian behavior. Assessment through direct observation is limited to those predetermined aspects of performance. Any hypothesis generated during data collection can only be tested through collection of additional measurements. On the other hand, where performances are video recorded, hypotheses can be tested through reanalysis of the same performances. Besides complementing MOE's for a particular study, a video library of driver performance can be established for use by other researchers.	5.6

Table 63. Expert Panel recommendations for future research on intersection geometric design, operations, and traffic control devices (Continued).

Rank	Statement of Research Need	Mean Ranking
4	Subjects perform certain behaviors, but we don't always know why. There is a need to study to what extent varying (gap) decisions are based on diminished capabilities versus differences in risk taking, and other factors, such as the presence of following vehicles. Ask subjects on what basis they make their decisions when we ask them to respond. Use a standardized psychological assessment for risk perception.	6.0
5	Obtain population-based (normative) measures of turning-driver positioning behavior across specified geometries to pinpoint positioning as a function of sight distance. Use naturalistic observation, with overhead video survey surveillance (two cameras) and add a side-of-road camera for driver observations.	6.2
6	Investigate traffic control systems (TCS) options to improve mobility of older drivers, such as sensor inputs to traffic control devices and operations (e.g., when a sensor detects vehicles queued to turn left at the end of a permissive green, employ a short green arrow to clear the intersection; this already occurs in Washington State using lag-left timing). Employ devices and loop detectors upstream to indicate to drivers what is happening. Investigate the utility of highway advisory radio (HAR)-type messages to pedestrians regarding crossing-cycle timing and traffic movements to watch for [e.g. "You have just pushed the crossing button. Please wait for the white 'walk' indication before crossing, which will happen in x seconds. When you cross, watch for traffic (turning from x or approaching on your left/right). When the walk signal flashes, you have x seconds to finish your crossing to (the first median/to the curb across the street)."]	7.5
7	Review intersection design process and priorities with respect to the consequences to pedestrians. The current criteria and controls are governed by capacity and mobility for drivers, but these work against pedestrians' needs. Consider determining a pedestrian "level of service" criteria.	7.9
8 (tie)	Study the tradeoff of head-on view of opposing through traffic provided by positive offset, which allows for more sight distance, but less accurate determination of time to collision, with a side view of approaching target provided by aligned offset, which reduces sight distance, but allows for more accurate speed-distance judgments. This can be accomplished in a laboratory study.	8.8

Table 63. Expert Panel recommendations for future research on intersection geometric design, operations, and traffic control devices (Continued).

Rank	Statement of Research Need	Mean Ranking
8 (tie)	Study older driver use and perception of two-way left-turn lanes, using naturalistic observation to record use.	8.8
10	Study the delineation aspects of channelization to determine what the effects are of varying forms of channelization delineation on left turns, and the extent to which roadway markings influence driver positioning. Study the effects of painting median curbs on pedestrian comfort and visibility to drivers (especially at night) where the island may become an obstacle. Delineation around medians wears off, but painting the curbs keeps median visibility high.	9.1
11	Study channelized versus non-channelized intersections to obtain descriptions of driver and pedestrian interactions (for right turns), as a function of design and operations.	9.2
12	Study innovative markings (stop lines, tracking paths) for complex intersections.	9.6
13	Conduct a before/after study of older pedestrian and older driver accidents as a function of intersection lighting, as well as the effects of improved lane boundary visibility through the use of RPM's on pavement and curbs.	9.8
14	Study the effects of raised islands in unorthodox placement on inappropriate movements by turning drivers and pedestrian inattention to traffic coming from an unexpected direction [e.g., what are the implications of raised islands used for full positive offset on side-street traffic turning left (potential for wrong-way movements into the left-turn bay)? What are the effects of the raised median used in the full positive offset on pedestrians who have the expectation that once they have reached the median, they have cleared one direction of traffic?].	10.0
15	Study the effects of "risk compensation" under enhanced designs. For example, will violations of traffic control device indications (e.g., RTOR prohibitions) increase as intersection geometry is altered to afford better visibility of conflicting traffic and/or ease of maneuver execution?	12.4

DEVELOPMENT OF RECOMMENDATIONS FOR GEOMETRIC AND OPERATIONAL CHANGES AT INTERSECTIONS

In this section, a sight distance analysis is reported that leads to recommendations for geometric and operational changes at intersections keyed to the particular needs of older drivers. A related concern for older pedestrians' safety in intersection use is also reflected in these recommendations. Building upon the prior sight distance design review and the approach recommended by the Older Road User Expert Panel, this effort is exclusively concerned with sight distance requirements for a driver performing a left-turn from a major roadway at an at-grade intersection with tangent approaches. Design recommendations will be developed for the amount and direction of the offset of opposite left-turn lanes, supplemented by countermeasures involving traffic operations or the use of traffic control devices to mitigate sight distance problems where changes in intersection geometry are not feasible.

To support the recommendations that follow, a rationale for the sight distance analysis is provided that reiterates the central issues, and summarizes and interprets the most pertinent data available from this and other research. Results of the laboratory and field data collection efforts in this project with the strongest statistical and operational significance are incorporated as appropriate. Furthermore, the validity of the prevailing model (Case V) for design calculations as found in the AASHTO (1994) *Green Book* is also questioned in terms of its applicability to the driving task demands in the left-turn maneuver situation of interest, and alternative (gap-acceptance) models are examined.

Recommendations pertaining to selected geometric elements other than opposite left-turn lane alignment are also provided at the end of this section to the extent that present findings are in agreement with the technical literature in this area, and such recommendations were endorsed by the collective judgment of the experts assembled to critique this work.

RATIONALE FOR SIGHT DISTANCE ANALYSIS

A fundamental premise for intersection design that surfaced in the Older Road User Expert Panel meeting is that it is not opposite left-turn lane offset *per se*, but rather the sight distance that a given level of offset provides, that should be the focus of recommendations in this project. More to the point, a specific design value for required offset is something the practitioners in this group decidedly did *not* want to see emerge from this effort. At the same time, panelists also raised the question of whether a gap-acceptance model would be more appropriate for the intersection case under consideration in this research. Perhaps most important was the question of the "intersection case" itself. The panelists' comments identified the following critical issue:

> *Should the sight distance requirements be based on assumptions and equations used by AASHTO for the Case IIIA (crossing maneuver at a stop-controlled intersection) or Case V (stopped vehicle turning left from a major highway), which are both based on the same formula* [$SD=1.47\ V\ (J+t_a)$]*, or should a new case be developed which more accurately reflects the driver's task of searching for gaps in the oncoming through-traffic stream?*

This critical design issue is addressed in the present analysis following an overview of project findings also reflected in this work.

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 results are discussed below, leading to a statement of recommendations for the offset of opposite left-turn lanes, plus operational countermeasures which are beneficial to older road users where geometric (re)design is not feasible due to right-of-way limitations or other reasons.

In a driving simulator study performed for the current project, four levels of left-turn lane offset were evaluated (3.7-m [12-ft] "full positive," 1.8-m [6-ft] "partial positive," 0-m [0-ft] "aligned," and -1.8-m [-6-ft] "partial negative") by drivers in three age groups (25-45, 65-74, and 75+). Other manipulated variables included three oncoming vehicle speeds (56.3, 72.4, and 88.5 km/h [35, 45, and 55 mi/h]), two types of oncoming through and opposite left-turning vehicles (passenger car and semi-tractor trailer), and the size of the presented gap (30.5 to 274 m [100 to 900 ft], in 30.5-m [100-ft] increments, between successive through vehicles). The findings of the laboratory study included:

- 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.
- An increase 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.
- A decrease in mean least safe gap size with increases in oncoming vehicle speed.
- 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).

In a field study conducted as part of the same project, drivers in the same three age groups made left turns at intersections with four levels of opposite left-turn lane offset (1.8-m [6-ft] "partial positive," 0-m [0-ft] "aligned," -0.91-m [-3-ft] "partial negative," and -4.3-m [-14-ft] "full negative"). 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 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 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.

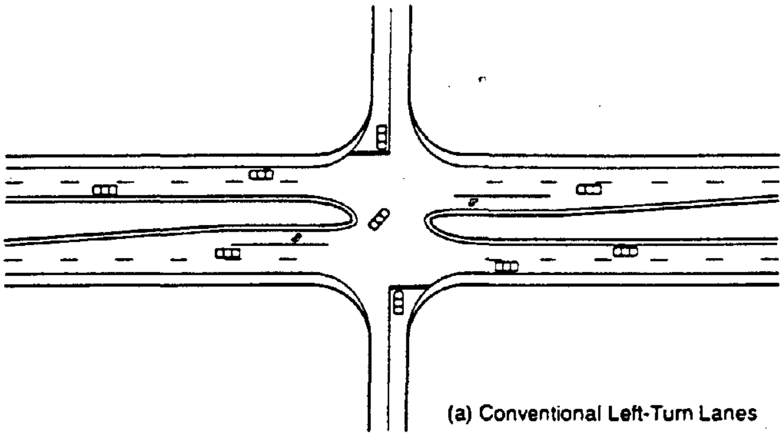
In the analysis of the field study lateral positioning data, it was found that the partial positive offset and aligned locations had the same effect on the lateral positioning behavior of drivers. At the same time, drivers moved approximately 1.5 m (5 ft) to the left when there was a large negative offset (-4.3 m [-14ft]), clearly indicating that sight distance was limited. There was also a significant difference between the partial negative offset geometry (-0.91 m [-3 ft]) versus the partial positive offset and aligned geometries, suggesting a need for longer sight distance 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.

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 112.7 km/h (70 mi/h).

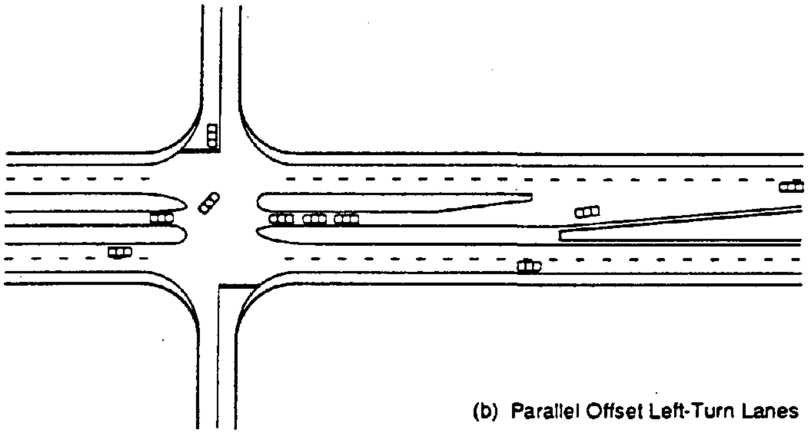
In a recent study of median intersection design, Harwood, Pietrucha, Wooldridge, Brydia, and Fitzpatrick (1995) state that wider medians generally have positive effects on traffic operations and safety; however, at suburban signalized and unsignalized intersections, accidents and undesirable behavior increase as the median width increases. At suburban intersections, it is therefore suggested that the median generally should not 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 45 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 (ADT) (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 the major road where only one left-turn lane in each direction of travel is needed for capacity.

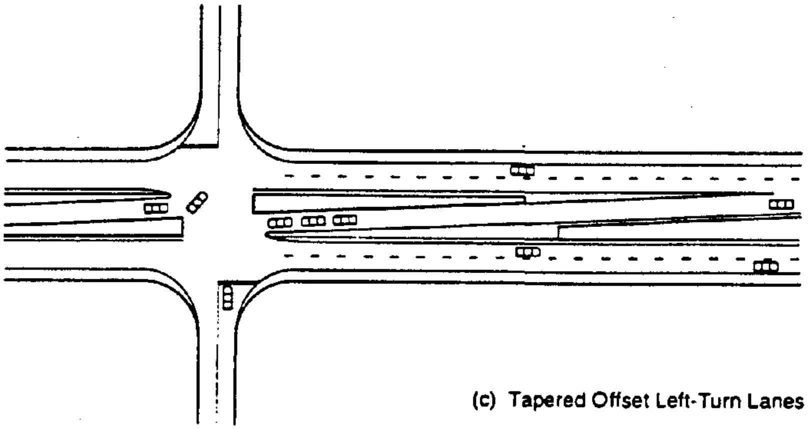
Because the accident rate at suburban signalized intersections increases as the median width increases, Harwood et al. (1995) suggest that suburban signalized intersections can generally operate effectively with median widths less than 7.6 m (25 ft) and that medians wider than 7.6 m (25 ft) are not generally recommended at suburban signalized intersections unless required for the selected left-turn treatment. In their report, a table of feasible allocations of available widths 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 7.8 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



(a) Conventional Left-Turn Lanes



(b) Parallel Offset Left-Turn Lanes



(c) Tapered Offset Left-Turn Lanes

Figure 45. Alternative left-turn treatments for rural and suburban divided highways. [Taken from Bonneson, McCoy, and Truby (1993); in Harwood et al. (1995).]

(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.

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.

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 tail lights 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 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, PRT, and differences in performance as a function of driver age, which underlies 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:

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

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

Field data were collected in the NCHRP study to better quantify the gap acceptance behavior of passenger car and truck drivers, but only for left- and right-turn 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 (67.1 m [220 ft]) at a 32.2-km/h (20-mi/h) design speed to 15.2 s (475.5 m [1,560 ft]) at a 112.7-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. 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. Younger subjects accepted shorter gaps than older subjects. The 50 percent gap acceptance point was about 7 s (i.e., if a gap is 7 s long, only 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 56.3 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 56.3 km/h (35 mi/h), while critical gaps for drivers age 75+ ranged from 5.8 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 Alexander, "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*. Alexander (1989) 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-turn 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 25.6 to 32.3 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 32.3 m (106 ft) at the -4.3-m (-14-ft) offset location; 6.4 s to travel 29.9 m (98 ft) at the -0.91-m (-3-ft) offset location; 6.6 s to travel 25.6 m (84 ft) at the aligned location; and 5.7 s to travel 26.8 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 29.9 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. These 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 guides.

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:

$$\mathrm{ISD} = 1.47V(J + t_a) \qquad \textbf{Model 1}$$

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, which 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:

$$\mathrm{ISD} = 1.47VG \qquad \textbf{Model 2}$$

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:

$$\mathrm{ISD} = 1.47V(J + t_a) \qquad \textbf{Model 3}$$

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 (Model 1). 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 instant 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 36, 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+ 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.

$$ISD = 1.47VG \qquad \textbf{Model 7}$$

where: V = design speed on the major road (mi/h).
G = critical gap (s) for drivers age 75 and 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 64. Perhaps the most significant result is the dramatic decrease in required sight distance that occurs with the gap model as 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 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 that 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 that 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 that exceeded the required distances based on the critical gaps of all drivers at two of the three intersections. The third intersection, which had 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 that were 10 percent greater than those produced by the proposed model, while the negatively offset location produced distances that 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

Table 64. Required sight distance for the negative 0.91-m (3-ft) offset, aligned, and positive 1.8-m (6-ft) 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

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. As an additional consideration, 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 degree of 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, especially for older drivers. Prior work by McCoy et al. 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 46 and can be expressed as follows:

$$SD_a = Y_a + Y_b$$

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).

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 46:

$$Y_b = \frac{(Y_a + Y_i)(X_r + 0.5\,L_w)}{X_i - X_r - X_o}$$

where: Y_i = longitudinal distance from the front of the left-turning vehicle to the driver's eye (ft); assumed to be 3.0 m (10 ft) from the 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:

$$X_r = L_w - V_w - X_l.$$

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 from the 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.

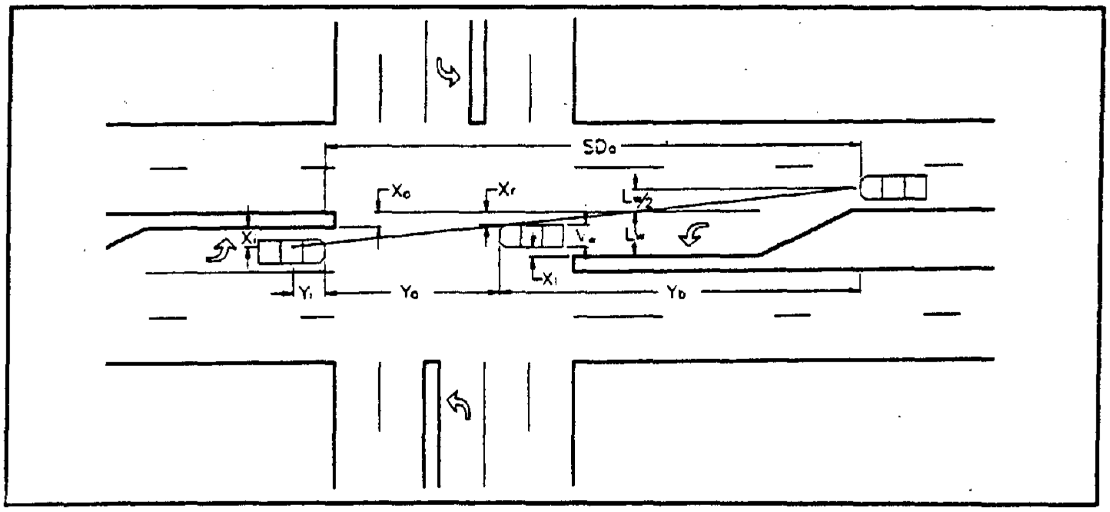


Figure 46. Available sight distance.
[Taken from McCoy, Navarro, and Witt (1992).]

Shown in Table 65 are the values for each of the variables in the equation and the resulting sight distance equations for each of the intersections. By setting these equations for available sight distance 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 above). The resulting offsets are shown in Table 66. Overall, the vehicle positionings requiring the largest amount of offset, in order, were:

(1) Unpositioned left-turning car/Unpositioned opposing left-turning truck.
(2) Unpositioned left-turning car/Unpositioned opposing left-turning car.
(3) Unpositioned left-turning car/Positioned opposing left-turning truck.
(4) Positioned left-turning car/Unpositioned opposing left-turning truck.
(5) Unpositioned left-turning car/Positioned opposing left-turning 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-turning 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 47 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 0.1 m (0.5 ft) for a 32.2-km/h (20-mi/h) design speed to 1.1 m (3.5 ft) for design speeds of 96.6 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 32.2-km/h (20-mi/h) design speed to 1.5 m (5.0 ft) for design speeds of 80.5 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 67 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 47 above 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 above), which may replace the current AASHTO model. The resulting offsets produced from this model are shown in Table 68. 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 48.

Table 65. Available sight distance at the negative 0.91-m (3-ft) offset, aligned, and positive 1.8-m (6-ft) offset locations observed in the field study.

Offset Condition (-3 ft)	Y_i	L_w	V_w	Y_a	X_l	X_l	X_r	X_l-X_r	Y_a+Y_i	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_i	L_w	V_w	Y_a	X_l	X_l	X_r	X_l-X_r	Y_a+Y_i	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_i	L_w	V_w	Y_a	X_l	X_l	X_r	X_l-X_r	Y_a+Y_i	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-turning 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-turning vehicles.

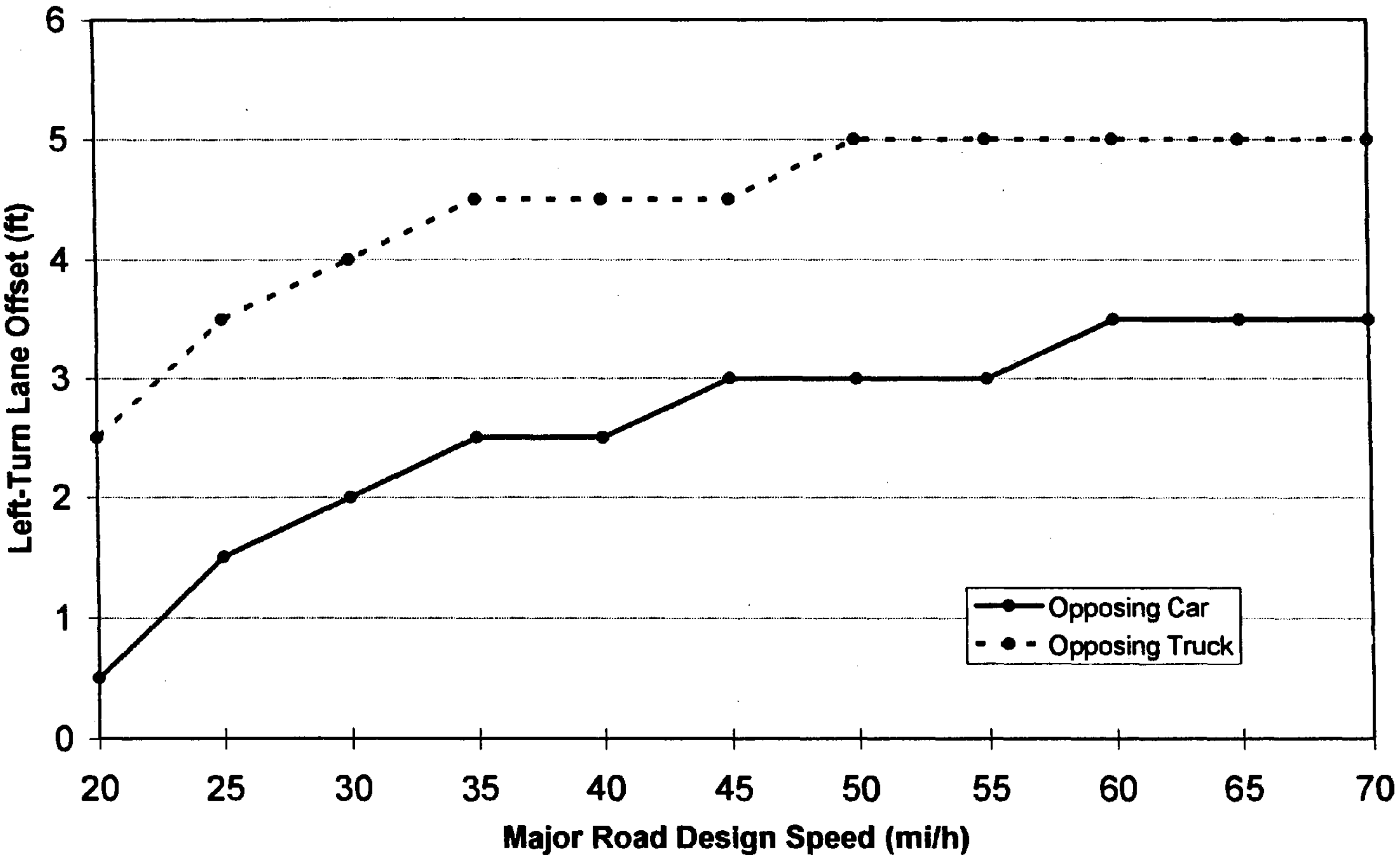
Table 66. Offsets necessary for achieving required sight distances, using the AASHTO model with field data maneuver times (t_a) and J=2.0 s.

Offset Condition (-3 ft)	ASD	RSD	Xo =	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_o))	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_o)}	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_o)}	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_o)}	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_o)}	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_o)}	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_o)}	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_o)}	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_o =	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_o)}	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_o)}	6.67V	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_o)}	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_o)}	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_o)}	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_o)}	8.67V	3.8 - {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_o)}	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_o)}	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_o =	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_o)}	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_o)}	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_o)}	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_o)}	11.32V	4.1 - {676.8/(11.32V-84.0)}	-0.7	0.7	1.5	1.9	2.3	2.5	2.7	2.8	3.0	3.1	3.1
Positioned/Positioned Truck	30.6 + {318.7/(1.4-X_o)}	8.67V	1.4 - {318.7/(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_o)}	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_o)}	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_o)}	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 47. 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 67. 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

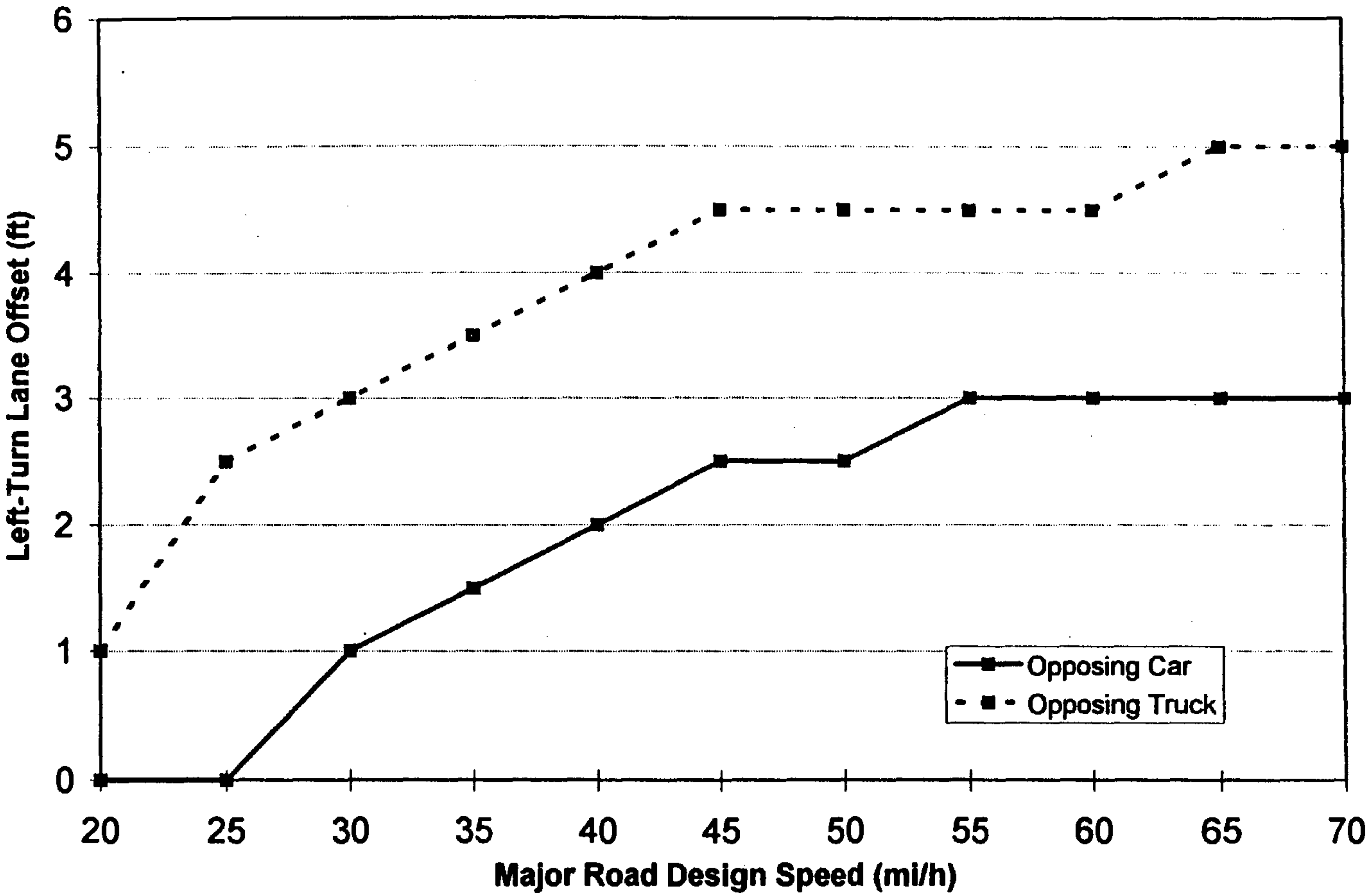
Table 68. Offsets necessary for achieving required sight distances using the proposed gap model.

				Offset (ft) by Design Speed (mi/h)										
Offset Condition (-3 ft)	**ASD**	**RSD**	**X_o =**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**
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 48. Design values for left-turn lane offsets to achieve the required sight distances computed from the proposed gap model.

The minimum offsets required to achieve the required sight distances produced from this model ranged from 0 m (0 ft) for design speeds of 32.2 and 40.2 km/h (20 and 25 mi/h) to 0.91 m (3.0 ft) for design speeds of 88.5 km/h (55 mi/h) and greater when the opposing left-turn vehicle is a car. When the opposing vehicle is a truck, the design offset values range from 0.3 m (1.0 ft) for a design speed of 32.2 km/h (20 mi/h) to 1.5 m (5.0 ft) for design speeds of 104.6 km/h (65 mi/h) and greater.

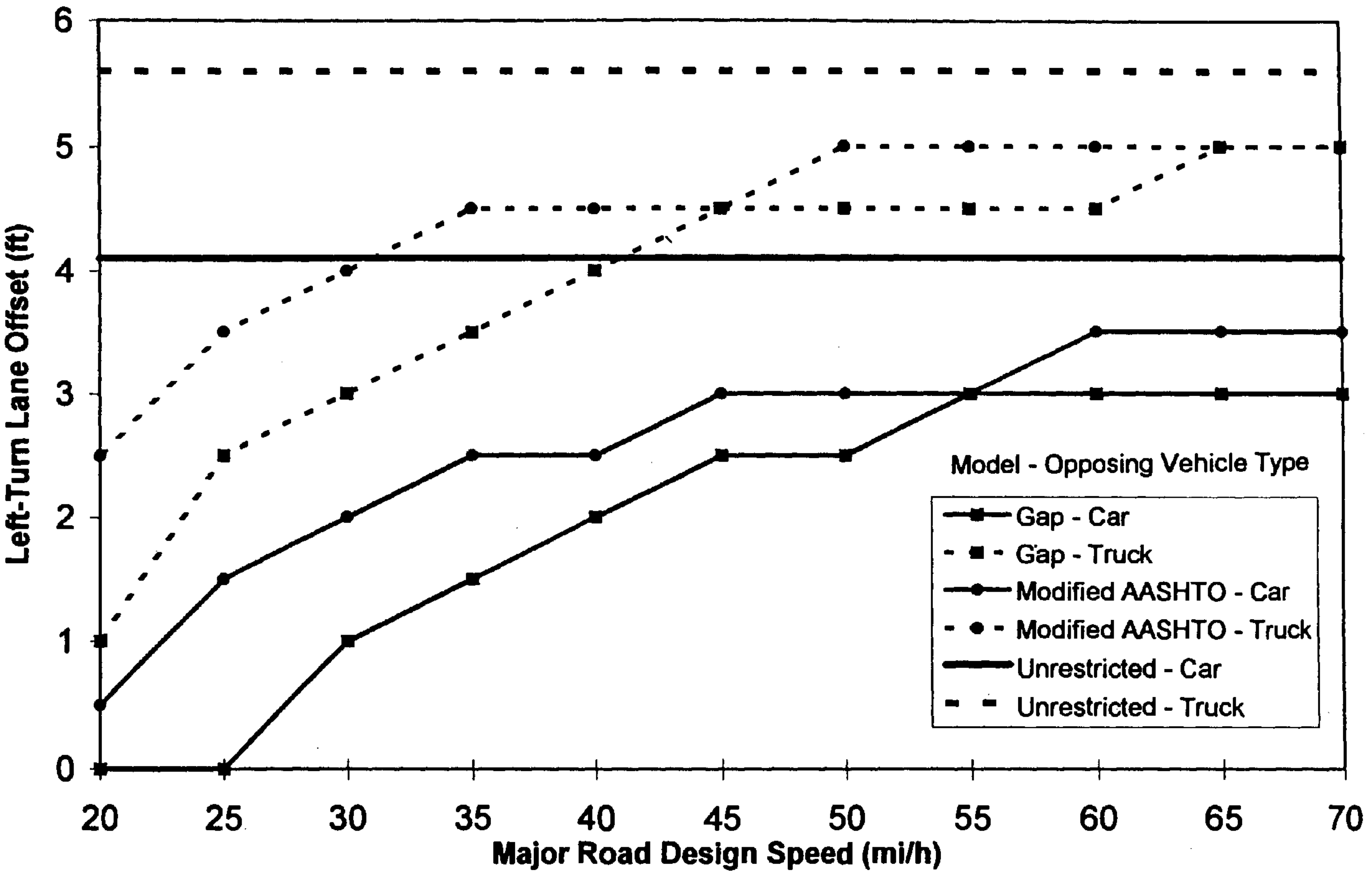
By plotting the design values from the AASHTO models and the gap model together, as shown in Figure 49, the effect of the smaller required sight distances produced by the gap model on the amount of offset needed can be shown. For example, when designing a 40.2-km/h (25-mi/h) roadway, the left-turn lane 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 80.5 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).

RECOMMENDATIONS FOR DESIGN

Based on this analysis, it is recommended that unrestricted sight distances and corresponding left-turn lane offsets be used in design when possible. At intersections where there are large percentages of left-turning trucks, the offsets required for opposing left-turning trucks should be used. Where unrestricted sight distances are not feasible, the ISD values computed using the modified AASHTO model should be used for design purposes. These distances generally will exceed the distances required to accommodate 95 percent of left-turning drivers, 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. Consequently, the left-turn lane offsets derived using this model (see Figure 49, modified AASHTO curves) should be used to achieve these sight distances where feasible.

If the gap model is accepted as the appropriate model for computing ISD for left-turning vehicles off a major roadway, further research needs to be conducted to evaluate the potential for problems for older drivers. The analyses conducted above showed the critical gaps for older drivers (age 75 and older) to be greater than the proposed critical gap in the model. These reduced sight distances obtained with the proposed gap model may present significant problems for older drivers, who have been shown to require larger gaps.

A further recommendation applies 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 [see Figure 45 (b) and (c)].



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

Figure 49. 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.

Proper signing (advance DIVIDED HIGHWAY CROSSING signs, and proper positioning of DIVIDED HIGHWAY, WRONG WAY, DO NOT ENTER, and ONE WAY signing at the intersection) must be implemented and pavement markings that scribe a path through the turn are recommended to reduce the likelihood of this wrong-way movement. In addition, a wide (61-cm [24-in]) white stop bar should be placed at the end of the channelized left-turn lane and white pavement lane-use arrows and wrong-way arrows should be placed within the left-turn lane according to the MUTCD requirements for expressway signing, as specified in sections 2E-40 and 2E-43.

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 geometric solutions are intractable.

(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 hours).

(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).

SUMMARY AND CONCLUSIONS

In summary, the objective in this project was to identify changes in the geometric design and operations at intersections that would have the greatest potential to aid in the safety and mobility of 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, and field observations) was then conducted to better define older persons' difficulties in intersection use. Next, an expert panel met to prioritize variables for more extensive laboratory and field studies. As a result of this effort, priorities for the variables to be investigated in the major research studies in the project were established. It was determined that the subsequent laboratory and field studies would focus on age, including both "young-old" (ages 65-74) and "old-old" (age 75+) groups, and the effects of alternative opposite left-turn lane geometry (offset amount and direction), right-turn channelization treatments and curb radius, and median pedestrian refuge island configurations, using both objective (performance) and subjective measures.

Data were obtained from laboratory (driving simulator) studies using dynamic, large-screen (correct size and perspective) views of dynamic driving scenes at intersections, where subjects' left-turn gap decisions could be measured as a function of a range of key operational factors. Data were also obtained from field studies that overlapped the laboratory measures, as well as providing additional measures of driver and pedestrian behavior at intersections. The findings and methodology of the project's major empirical efforts are contained in the chapter titled, "Laboratory and Field Investigations" in this report volume. Supplementing the empirical findings, a sight distance analysis was performed, and sight distance requirements based on maneuvers observed in the field were compared to distances indicated by a variety of models, including traditional ISD models, a modified AASHTO model, and gap acceptance models exercised in NCHRP Project 15-14(1).

A critique of the present study findings and analyses was provided to the project team during a second expert panel meeting. This project activity concluded that sufficient evidence from this and related research 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.

The principal conclusions that have been drawn from this work include the recommendations for intersection design and traffic control practices described in the highlighted items A through D, as follows, plus a set of operational countermeasures where geometric design changes are not feasible. Other conclusions from this work address priorities for future research in this area; these are described in the concluding chapter of this report.

Intersection design **Recommendations A and B,** stated below, will be most helpful in accommodating the needs and capabilities of older road users.

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

B. 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.

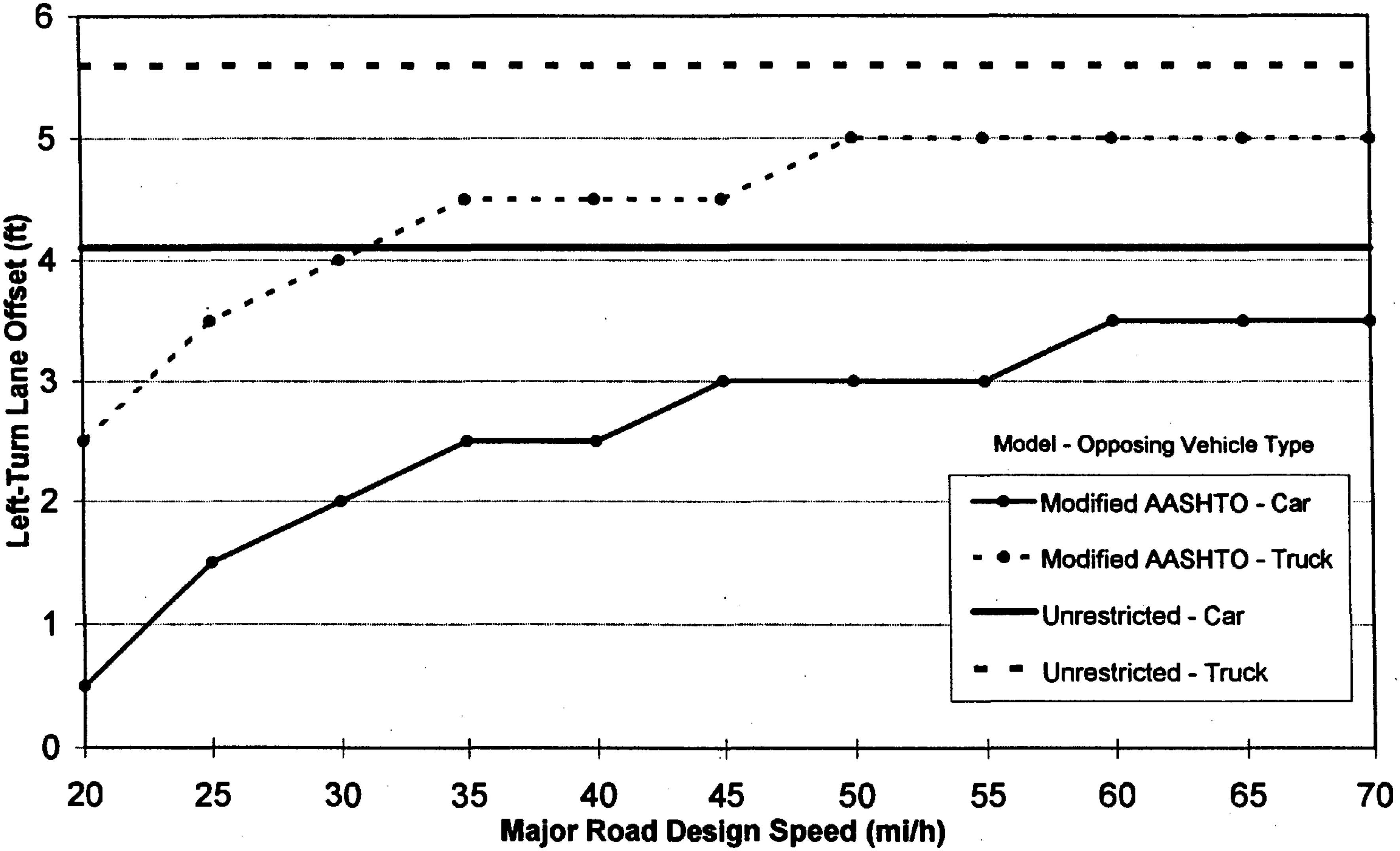
It is recognized that a number of factors may prohibit the provision of unrestricted sight distance in a given location. Under these circumstances, as stated in **Recommendation C** below, the ISD values computed using the modified AASHTO model should be used for design purposes. These distances generally 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 50.

C. 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:

$$\mathbf{ISD = 1.47V(J + t_a)}$$

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 performed in this project 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 50. Recommended left-turn lane offset design values.

Further recommendations apply to channelized offset left-turn lanes. A particular concern 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. **Recommendation D** describes countermeasures 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 51.

D. 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 that scribe a path through the turn are recommended to reduce the likelihood of a 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.**

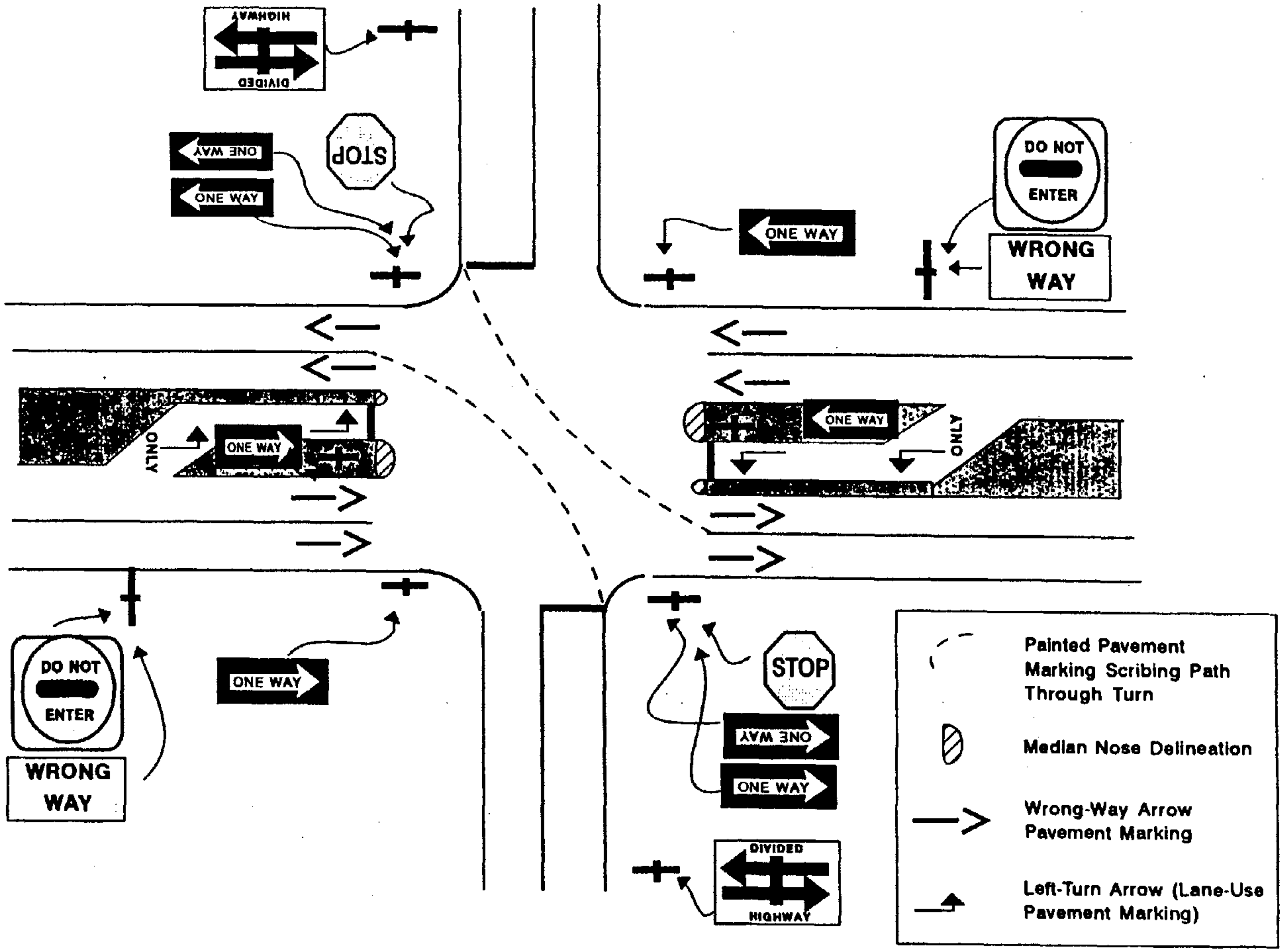


Figure 51. Recommended signing and delineation treatments for intersections with channelized left-turn lanes to reduce the potential for wrong-way movements for drivers turning left from the minor roadway.[1]

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[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 farther away from turning into the channelized left-turn lane; and (2) it maintains separation between the paths of opposing left-turning drivers.

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/or 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 hours).**

(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).**

FUTURE RESEARCH PRIORITIES

This report concludes with recommendations for future research priorities to support intersection design and operational changes with the greatest potential to benefit older drivers and pedestrians. To a large extent, these recommendations reflect the opinions of the Older Road User Expert Panel, as described earlier. In addition, intersection negotiation difficulties of older persons and the most effective remedies as perceived by this group in one or more of the problem identification studies in this project were an important source of candidate research issues. Finally, a consideration of emerging Intelligent Transportation Systems (ITS) technologies, which, if reliable, present a strong potential to ameliorate documented difficulties of older road users at intersections, suggested further avenues for research that are expected to benefit both safety and capacity.

Five recommendations for future research topics were developed:

(1) Develop Ecologically Valid Models of Pedestrian Crossing Behavior at Intersections.
(2) Identify and Determine the Relative Importance of Factors Influencing Driver Gap Decisions at Intersections.
(3) Driver Demand as a Figure-of-Merit for Proposed Highway Engineering Countermeasures.
(4) Implement and Evaluate Technologies for Active Traffic Control at Intersections.
(5) Implement and Evaluate Technologies for Active Pedestrian Control at Intersections.

The recommended topics for future research are not intended to address all of the specific elements of geometry, operations, or traffic control practices that could significantly affect user behavior at intersections. Neither does the order of presentation of the research priorities necessarily connote their relative urgency. Instead, it is assumed that targeted design elements will be finalized in subsequent development of detailed problem statements by the sponsoring agency; and, it is expected that further work in *all* of the recommended areas will lead to implementable changes to current practice that satisfy the widely recognized needs of older drivers and pedestrians, while increasing the overall safety and efficiency of the highway system. A statement of the research need, a recommended measurement approach, and a statement of the anticipated benefits are provided for each research priority identified below:

(1) Develop Ecologically Valid Models of Pedestrian Crossing Behavior at Intersections

Research Need

Measure the effect on pedestrian crossing behavior of intersection geometric and operational elements, for identified demographic groups, in particular settings; specifically, determine what are the relative contributions of situational factors and individual differences to variability in: (a) pre-movement search behaviors, (b) the crossing decision, and (c) the nature of pedestrians' movements during crossing, versus changes in geometric features, traffic control devices, and/or pavement markings.

Recommended Measurement Approach

An observational field study, with video recording of dependent variables across an extensive and diverse set of locations, should be conducted to obtain objective data for all MOE's; plus, structured interviews with a sample of pedestrians at each observation site (selected according to demographic and situational criteria) should be conducted to obtain subjective data, as inputs to analyses of covariance with objective MOE's and to aid in interpretation of differences associated with geometric and operational elements.

Anticipated Benefits

An understanding of the extent to which changes in specific aspects of intersection geometry and operations can be expected to influence pedestrian safety and mobility, leading to guidelines for countermeasure development and warrants for where and under what conditions the implementation of engineering changes will be most cost-effective.

(2) Identify and Determine the Relative Importance of Factors Influencing Driver Gap Decisions at Intersections

Research Need

Measure to what extent inappropriate decisions to initiate turning movements across traffic are explained by diminished capabilities, individual differences in risk-taking (risk acceptance), and the actions of other motorists, as opposed to problems with the design of geometric elements or the traffic control practices *per se*; specifically, determine the effect on drivers' gap decisions and resulting behaviors (gap acceptance/rejection, critical gap size, turning path errors, clearance time) of differences in intersection geometry, operations, and demographic and situational factors *in combination*.

Recommended Measurement Approach

A simulation of an intersection approach under controlled laboratory conditions where various geometric elements and traffic control device applications can be manipulated should first be completed to assess the effects on gap decisions *without* other sources of variability. Next, a controlled field study should be conducted with a sample stratified to represent a meaningful range of risk acceptance and (diminished) driving skills within the current and projected population; this study should employ video recording of turning movements through the intersection from a fixed camera location, plus dynamic, driver's perspective views of downstream (opposing traffic) conditions, at a sufficient number of locations, to sample varying levels of geometric treatments and differences in traffic control practices under varying operational and environmental conditions.

Anticipated Benefits

An understanding of the extent to which changes in specific aspects of intersection geometry and operations can be expected to influence driver gap decisions and the safety of turning movements, leading to guidelines for countermeasure development and warrants for where and under what conditions the implementation of engineering changes will be most cost-effective.

(3) *Driver Demand as a Figure-of-Merit for Proposed Highway Engineering Countermeasures*

Research Need

Quantify the workload associated with the approach to and negotiation of intersections with varying geometric and operational characteristics, establishing baselines for each member of a sample representing the 5th to 95th percentile range for selected sensory/perceptual and cognitive capabilities; then, develop a metric indicating reduction in workload—accounting for the individual differences in functional capability—associated with engineering countermeasures widely cited as facilitating intersection negotiation (e.g., higher conspicuity for raised surfaces on median islands, channelizing islands, and corner curb lines; and overhead signing for lane assignments).

Recommended Measurement Approach

A comprehensive functional assessment of drivers of different ages, including young/novice drivers through the "old-old" (75+) age cohort, is necessary to first characterize the test sample for later regression against workload measures. Workload measures should be obtained using multiple tasks under divided-attention conditions, where the primary task involves aspects of vehicle control approaching and moving through the intersection, the secondary task involves a continuous serial processing requirement, and where real-time monitoring of visual search behavior (gaze orientation and fixation time) is performed. A two-phase data collection effort is recommended, initially using dynamic laboratory simulation to obtain measures for a large number and combination of design elements, followed by controlled field testing in a (subject's own) vehicle instrumented to obtain the desired vehicle control and driver response data.

Anticipated Benefits

Understanding of the causes of driver errors at intersections, while developing a means to quantify the potential benefit in terms of variables mediating crash risk (e.g., improved detection of peripheral conflicts) permitted by a reduction in primary task workload from given engineering countermeasures.

(4) *Implement and Evaluate Technologies for Active Traffic Control at Intersections*

Research Need

Test the effectiveness of active traffic control system devices at intersections (e.g., sensors to detect vehicles queued in intersection at end of permissive green phase; sensors to detect through vehicles moving at high speed that oppose left-turning traffic during permissive green phase, regardless of sight distance for turning vehicles; sensors to detect the presence of opposing through vehicles within a given distance of the intersection where sight distance is restricted for left-turning vehicles by geometry or by vehicles in opposite turn lane).

Recommended Measurement Approach

Initial development/selection of algorithms to process sensor input to select from a library of traffic control messages is required. A laboratory simulation to identify the best message format and content among display options for all messages should follow, using samples representative of the current and projected driving population; in-vehicle signing alternatives should be considered, in addition to highway hardware, for communication with motorists. A controlled field study using a (subject's own) vehicle instrumented to obtain measures of vehicle control and driver response (including real-time visual search indices) during the approach to and negotiation of intersections at which the experimental systems have been installed is then recommended to finalize the human factors specifications for each application of active traffic control technology. An observational field study at matched sites will then be appropriate to gauge the effect on operations for a large sample of motorists, and to estimate the impact of introducing this technology on a system-wide basis at warranted locations.

Anticipated Benefits

Improvements in safety and capacity resulting from better movement of traffic—especially turning traffic—through intersections, compensating for age-related diminished capabilities and information deficits from obstructed sight distance through enhanced sensing and real-time feedback to drivers of high-potential conflict situations.

(5) *Implement and Evaluate Technologies for Active Pedestrian Control at Intersections*

Research Need

Test the effectiveness of active pedestrian control devices at intersections (e.g., voice instructions at curb where two-stage crossings are designed, and to advise pedestrians of turning traffic that conflicts with crossing movements; visual and/or auditory displays of time remaining before onset of steady DON'T WALK prohibitory signal phase).

Recommended Measurement Approach

A laboratory simulation to identify the best message format and content among display options for all messages should first be performed, using test samples representative of the current and projected driving population. A controlled field study to obtain measures of user comprehension and acceptance (credibility) and to confirm preferred presentation modes (visual versus auditory) for message elements is then recommended to finalize the human factors specifications for each application of active pedestrian control technology. An observational field study at matched sites will then be appropriate to gauge the effect on operations for a large sample of pedestrians and to estimate the impact of introducing this technology on a system-wide basis at warranted locations.

Anticipated Benefits

Improved safety and mobility of pedestrians, facilitating intersection crossing movements by compensating for age-related diminished capabilities in the awareness of conflicts and for uncertainty (lack of confidence) at the time a crossing decision must be made about reaching a protected location (median or opposite curb).

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TASK 2.0: MAINTAIN CORRECT LATERAL LANE POSITION	
Look Location	• Straight ahead at center of lane, making confirmatory glances at lane markings and road edges as guidance cues.
Visual/ Perceptual Requirements	• Contrast sensitivity for low spatial frequency targets (lane lines and roadway edges). • An FHWA-sponsored research project demonstrated that older subjects required a 30 to 300 percent increase in stripe brightness to bring performance (correct detection of roadway heading) to a level commensurate with their younger counterparts (Staplin et al., 1990).
Cognitive Requirements	• Observe the rate and amount of sideslip (8.9 cm [3.5 in] of lateral movement is detectable) by detecting misalignment of objects in visual field with path of vehicle (objects directly along the vehicle path do not appear to move). • When lane is bordered on both sides by objects such as vehicles or islands, assess ability to pass between obstructions (gap acceptance). • Concurrent demands for lane selection, vehicle control for path maintenance, plus vigilance for potential conflicts with other vehicles and pedestrians (attention-switching).
Control Movements	• Correct errors in car heading by turning wheel in desired direction. • Decrease magnitude of steering corrections as car velocity increases.
Potential Errors	• Lane encroachments potentially resulting in sideswipe and/or head-on accidents. • Steering wheel reversals leading to a greater number of corrections/erratic steering. • Failure to focus well ahead to maintain vehicle within boundaries was a primary cause in 14 out of 1000 accident reports reviewed by McKnight and Adams (1970). • Increased attention to the task of steering a vehicle reduces the attentional resources that can be allocated to other tasks, such as detecting and reading signs, and responding to traffic in the periphery. Staplin et al. (1990) found age-related differences in drivers' ability to rapidly encode symbol and verbal messages contained in current signing practices while performing a subsidiary tracking task; older subjects demonstrated more incorrect responses in a Sternberg memory task, as well as no responses, under low tracking task difficulty, and an exaggerated rate of no-response outcomes when tracking difficulty was increased. In a divided-attention study by Brouwer, Ickenroth, Ponds, and Van Wolffelaar (1990), performance on a visual reaction time (RT) task for peripherally presented targets declined as subjects were instructed to concentrate on a tracking task. Older subjects showed a decline in dual-task performance in another study conducted by Ponds, Brouwer, and Van Wolffelaar (1988), where they simultaneously performed a tracking task and a visual performance task; only the visuomotor tracking task showed an age trend. • Reduced time to anticipate emergencies where alternative behavior ahead may be required (brake, steer left, or steer right). Older drivers had more difficulty than younger drivers in situations when they must alter their planned responses (Staplin et al., 1990; Stelmach, Goggin, and Amrhein, 1988).
Relevant Geometry or Operations	• Conspicuity of lane and edgelines, as well as that of curbs and median barriers.

TASK 3.3: SURVEY PAVEMENT MARKINGS

Look Location	• Left- and right-lane boundaries at least 1.75 s ahead (Zell, 1969 in McKnight and Adams, 1970). • Downstream (one city block) at painted channelization (right-turn storage lanes, left-turn bays, lane shifts, and lane drops), painted arrows, and painted messages in center of lane, designating lane restrictions and turning movements.
Visual/ Perceptual Requirements	• Contrast sensitivity for low spatial frequency targets. • Acuity to discern broken from solid lane lines, and to read messages painted on the pavement. • Older subjects participating in a focus group discussion as part of an FHWA-sponsored study reported difficulty knowing where to drive, due to missing or faded roadway lines on roadway edges and delineation of islands and turning lanes. They reported hesitating during turns because they didn't know where to aim the vehicle (Staplin et al., 1990). In another focus group, subjects suggested advance warning pavement markings located as far in advance of an intersection as practicable (Council and Zegeer, 1992).
Cognitive Requirements	• Concurrent demands for lane selection, vehicle control for path maintenance, plus vigilance for potential conflicts with other vehicles and pedestrians (attention-switching).
Control Movements	• Coordination of steering control movements with eye movements; maintaining speed of traffic flow.
Potential Errors	• Edwards and Hahn (1964) in McKnight and Adams (1970) reported that there was one instance of lane straddling per hour and one instance of crossing the center line per 2 hours. • Missed detection of a lane drop results in the requirement for a driver to perform a merge from a stopped position in the middle of the roadway into a densely spaced stream of traffic. At best, this impedes the traffic flow, and at worst, could result in a collision, depending on the gap acceptance judgment the driver makes, and following driver attention.
Relevant Geometry or Operations	• Delineation conspicuity and painted roadway message conspicuity and legibility. Presence of advanced warning signs would aid in focusing drivers' attention to the presence of lane shifts or drops. Advance lane control signs would provide (necessary) redundancy to painted arrows on road surface, and compensate for faded, missing, or covered (with snow) markings.

TASK 3.4: SURVEY PHYSICAL BARRIERS

Look Location	• Curb bordering right-lane edge; medians at left-lane edge separating direction of traffic; downstream medians forming left- and right-turn channelization and pedestrian refuges.
Visual/ Perceptual Requirements	• Contrast sensitivity for detection of raised pavement barriers.
Cognitive Requirements	• Gap judgments for maintaining vehicle in center of lane, possibly bordered by vehicles in adjacent lane on one side and barrier on other side. • Attention-switching required to monitor lane position, detect and negotiate barriers, detect and respond to peripheral vehicles and pedestrians.
Control Movements	• Coordination of steering control movements with eye movements; maintaining speed of traffic flow.
Potential Errors	• Missed detection or steering errors may result in collision with barrier, the severity of which is dependent on the barrier height, median width, and use of median as pedestrian refuge. At a minimum, the vehicle wheels will roll up barrier edge, and driver will correct error by steering back into lane. Collision with barrier may result in following traffic rear-ending vehicle if the vehicle abruptly stops upon impact. Collisions with pedestrians possible depending on grade.
Relevant Geometry or Operations	• Curb and median conspicuity (size and contrast between barrier as a target and its background, i.e., the pavement).

TASK 5.0: DETERMINE PROPER LANE POSITION

Look Location	• Signs mounted on shoulders, medians, overhead. • Painted roadway messages. • Downstream channelization. • Downstream traffic movement.
Visual/ Perceptual Requirements	• Contrast sensitivity, visual acuity, peripheral vision.
Cognitive Requirements	• Attention-switching, processing information from a variety of sources, decision-making.
Control Movements	• Coordination of steering control movements with eye movements; maintaining speed of traffic flow.
Potential Errors	• Per McKnight and Adams (1970), the desired lane should be entered no later than 30.5 m (100 ft) prior to reaching intersection. If all cues from TCD's have been missed, driver will end up in wrong lane, or may realize that he/she is in the wrong lane closer to the intersection than is safe to make a lane change. If the driver executes a lane change at this point, collision with other vehicles is possible. Failure to effect early entry into correct lane in order to safely negotiate a desired turn ahead was the primary cause of 6 out of 1000 accidents surveyed for the project. Edwards and Hahn (1964) observed that one turn from the wrong lane occurs per hour. This behavior inhibits the flow of traffic following the vehicle as it waits to change lanes very close to the intersection, as well as traffic in the desired adjacent lane, which may slow to let the driver enter the lane. This increases the potential for unsafe gap judgments to be made, causing rear-end collisions.
Relevant Geometry or Operations	• Lane delineation conspicuity. • Pavement marking legibility and conspicuity. • Conspicuity, legibility, and placement of traffic signs. • Conspicuity of downstream medians defining storage lanes. • Sight distance to intersection.

TASK 10.0: SEARCH FOR PATH GUIDANCE CUES FOR AIMING VEHICLE ACROSS INTERSECTION OR THROUGH TURNING MANEUVER

Look Location	<u>For crossing intersection:</u> Across intersection to verify position of opposing traffic lanes (double solid yellow lines or median), number of lanes across the intersection in the intended direction of travel (right edgelines and/or curbs, and solid or broken white lines dividing same-way traffic). <u>For turning left:</u> Left at median to determine required turning radius and at what point the wheel should be turned; at lane lines on the pavement in the center of intersection and those demarking lane(s) in the desired direction of travel beyond the intersection to determine the number of turning lanes and how soon a merge may be required if multiple turning lanes merge into a fewer number of traveling lanes. <u>For turning right:</u> Right at the curb and any center medians to determine required turning radius; at delineation in and beyond the turn to determine the number of turning lanes and when a merge may be required after the turn.
Visual/ Perceptual Requirements	• Contrast sensitivity for detecting pavement lines and medians.
Cognitive Requirements	• Ability to integrate information obtained from multiple visual locations (attention to other vehicles and pedestrians in the periphery, traffic signal phase, and roadway several seconds ahead) while maintaining speed of traffic flow, and correct vehicle heading and lateral position.
Control Movements	• Continued steering and speed adjustments as intersection is approached.
Potential Errors	• Missed detection of delineation separating directions of travel could result in head-on collisions. • Missed detection of barriers (medians and curbs) could result in impact with the barrier, resulting in vehicle damage, potential collisions with pedestrians, and impeding traffic flow with potential rear-end collision by following traffic. • Multiple turning lanes not well delineated could result in drivers not keeping within the proper lane during a turn. This could result in conflicts with traffic turning in the same direction in adjacent lanes. • Turning lanes which merge quickly on the other side of the intersection may result in conflicts between left-turning drivers and right-turning drivers entering the roadway from opposite directions.
Relevant Geometry or Operations	• Number of turning lanes; adequacy of delineation in and beyond intersection; conspicuity of median barriers and curbs.

APPENDIX B: CHI-SQUARE (χ^2) CONTINGENCY TABLES SHOWING OBSERVED AND EXPECTED COUNTS OF UNSAFE GAPS ACCEPTED BY SUBJECTS IN THE LABORATORY STUDY OF OPPOSITE LEFT-TURN LANE GEOMETRY

Chi-square two-way contingency table showing observed and (*expected*) values for counts of unsafe gaps accepted as a function of geometry and age group, with a blocking passenger car, collapsed across opposing vehicle type and speed.

	GEOMETRY				
DRIVER AGE	FULL POSITIVE	PARTIAL POSITIVE	ALIGNED	PARTIAL NEGATIVE	Total
25-45	100.81	100.00	74.75	75.40	350.96
	(84.43)	*(88.59)*	*(77.15)*	*(100.79)*	
65-74	70.00	77.60	58.67	85.11	291.38
	(70.10)	*(73.55)*	*(64.05)*	*(83.68)*	
75+	257.00	271.30	257.49	350.19	1136.00
	(273.29)	*(286.76)*	*(249.71)*	*(326.24)*	
Totals	427.81	448.90	390.90	510.71	1778.33

Chi-square two-way contingency table showing observed and (*expected*) values for counts of unsafe gaps accepted as a function of geometry and age group, with a blocking semi-tractor trailer, collapsed across opposing vehicle type and speed.

	GEOMETRY				
DRIVER AGE	FULL POSITIVE	PARTIAL POSITIVE	ALIGNED	PARTIAL NEGATIVE	Total
25-45	98.03	96.82	50.76	161.46	407.07
	(89.13)	*(90.71)*	*(83.00)*	*(144.23)*	
65-74	78.18	74.09	56.31	144.58	353.16
	(77.32)	*(78.70)*	*(72.01)*	*(125.13)*	
75+	259.42	272.46	298.60	398.89	1229.40
	(269.17)	*(273.96)*	*(250.66)*	*(435.58)*	
Totals	435.63	443.37	405.67	704.93	1989.63

Chi-square two-way contingency table showing observed and *(expected)* values for counts of unsafe gaps accepted as a function of geometry and age group, with a blocking passenger car and an opposing passenger car, collapsed across speed.

	GEOMETRY				
DRIVER AGE	FULL POSITIVE	PARTIAL POSITIVE	ALIGNED	PARTIAL NEGATIVE	Total
25-45	56.36 *(45.67)*	52.27 *(46.84)*	43.43 *(39.86)*	31.31 *(51.01)*	183.38
65-74	42.00 *(42.31)*	45.20 *(43.38)*	35.56 *(36.92)*	47.11 *(47.25)*	169.87
75+	156.52 *(166.91)*	163.91 *(171.17)*	143.48 *(145.68)*	206.28 *(186.44)*	670.19
Totals	254.88	261.39	222.47	284.70	1023.44

Chi-square two-way contingency table showing observed and *(expected)* values for counts of unsafe gaps accepted as a function of geometry and age group, with a blocking passenger car and an opposing semi-tractor trailer, collapsed across speed.

	GEOMETRY				
DRIVER AGE	FULL POSITIVE	PARTIAL POSITIVE	ALIGNED	PARTIAL NEGATIVE	Total
25-45	44.44 *(38.39)*	47.73 *(41.63)*	31.31 *(37.39)*	44.09 *(50.17)*	167.58
65-74	28.00 *(27.84)*	32.40 *(30.18)*	23.11 *(27.11)*	38.00 *(36.38)*	121.51
75+	100.48 *(106.70)*	107.39 *(115.71)*	114.01 *(103.93)*	143.91 *(139.45)*	465.80
Totals	172.93	187.52	168.43	226.00	754.88

Chi-square two-way contingency table showing observed and (*expected*) values for counts of unsafe gaps accepted as a function of geometry and age group, with a blocking semi-tractor trailer and an opposing passenger car, collapsed across speed.

	GEOMETRY				
DRIVER AGE	FULL POSITIVE	PARTIAL POSITIVE	ALIGNED	PARTIAL NEGATIVE	Total
25-45	48.49	55.91	25.00	87.73	217.12
	(45.88)	*(49.43)*	*(44.91)*	*(76.90)*	
65-74	41.78	41.20	29.20	82.80	194.98
	(41.20)	*(44.39)*	*(40.33)*	*(69.05)*	
75+	128.99	139.13	160.43	196.96	625.51
	(132.17)	*(142.41)*	*(129.39)*	*(221.53)*	
Totals	219.25	236.24	214.64	367.48	1037.61

Chi-square two-way contingency table showing observed and (*expected*) values for counts of unsafe gaps accepted as a function of geometry and age group, with a blocking semi-tractor trailer and an opposing semi-tractor trailer collapsed across speed.

	GEOMETRY				
DRIVER AGE	FULL POSITIVE	PARTIAL POSITIVE	ALIGNED	PARTIAL NEGATIVE	Total
25-45	49.55	40.91	25.76	73.74	189.95
	(43.17)	*(41.33)*	*(38.12)*	*(67.33)*	
65-74	36.40	32.89	27.11	61.78	158.18
	(35.95)	*(34.42)*	*(31.74)*	*(56.07)*	
75+	130.43	133.33	138.16	201.93	603.86
	(137.25)	*(131.39)*	*(121.18)*	*(214.05)*	
Totals	216.38	207.13	191.03	337.45	951.99

Chi-square two-way contingency table showing observed and *(expected)* values for counts of unsafe gaps accepted as a function of geometry and age group, with a blocking passenger car and an opposing passenger car traveling at 56 km/h.

GEOMETRY

DRIVER AGE	FULL POSITIVE	PARTIAL POSITIVE	ALIGNED	PARTIAL NEGATIVE	Total
25-45	2.27	5.00	2.53	2.53	12.32
	(2.66)	*(3.14)*	*(2.68)*	*(3.85)*	
65-74	2.80	7.20	5.78	9.33	25.11
	(5.41)	*(6.40)*	*(5.45)*	*(7.85)*	
75+	53.04	56.52	50.24	72.46	232.27
	(50.05)	*(59.18)*	*(50.42)*	*(72.62)*	
Totals	58.12	68.72	58.50	84.32	269.71

Chi-square two-way contingency table showing observed and *(expected)* values for counts of unsafe gaps accepted as a function of geometry and age group, with a blocking passenger car and an opposing passenger car traveling at 72 km/h.

GEOMETRY

DRIVER AGE	FULL POSITIVE	PARTIAL POSITIVE	ALIGNED	PARTIAL NEGATIVE	Total
25-45	20.91	17.73	16.67	10.10	65.40
	(17.23)	*(16.23)*	*(14.23)*	*(17.71)*	
65-74	16.40	13.60	10.22	12.89	53.11
	(14.00)	*(13.18)*	*(11.55)*	*(14.38)*	
75+	50.87	51.74	45.89	67.63	216.14
	(56.95)	*(53.65)*	*(47.01)*	*(58.53)*	
Totals	88.18	83.06	72.79	90.62	334.65

Chi-square two-way contingency table showing observed and (*expected*) values for counts of unsafe gaps accepted as a function of geometry and age group, with a blocking passenger car and an opposing passenger car traveling at 88 km/h.

	GEOMETRY				
DRIVER AGE	FULL POSITIVE	PARTIAL POSITIVE	ALIGNED	PARTIAL NEGATIVE	Total
25-45	33.18 *(27.38)*	29.55 *(27.63)*	24.24 *(22.98)*	18.69 *(27.67)*	105.66
65-74	22.80 *(23.75)*	24.40 *(23.97)*	19.56 *(19.93)*	24.89 *(24.00)*	91.64
75+	52.61 *(57.47)*	55.65 *(58.00)*	47.34 *(48.23)*	66.18 *(58.09)*	221.79
Totals	108.59	109.60	91.14	109.76	419.09

Chi-square two-way contingency table showing observed and (*expected*) values for counts of unsafe gaps accepted as a function of geometry and age group, with a blocking passenger car and an opposing semi-tractor trailer traveling at 56 km/h.

	GEOMETRY				
DRIVER AGE	FULL POSITIVE	PARTIAL POSITIVE	ALIGNED	PARTIAL NEGATIVE	Total
25-45	2.53 *(3.42)*	6.82 *(4.21)*	2.53 *(3.95)*	5.00 *(5.28)*	16.87
65-74	4.89 *(4.17)*	5.20 *(5.13)*	4.44 *(4.81)*	6.00 *(6.43)*	20.53
75+	33.82 *(33.64)*	38.70 *(41.38)*	40.58 *(38.79)*	52.61 *(51.90)*	165.70
Totals	41.23	50.71	47.54	63.61	203.10

Chi-square two-way contingency table showing observed and *(expected)* values for counts of unsafe gaps accepted as a function of geometry and age group, with a blocking passenger car and an opposing semi-tractor trailer traveling at 72 km/h.

	GEOMETRY				
DRIVER AGE	FULL POSITIVE	PARTIAL POSITIVE	ALIGNED	PARTIAL NEGATIVE	Total
25-45	19.70 *(15.13)*	16.82 *(15.89)*	9.60 *(13.21)*	17.73 *(19.61)*	63.84
65-74	7.56 *(9.34)*	12.40 *(9.81)*	6.67 *(8.16)*	12.80 *(12.11)*	39.42
75+	32.85 *(35.64)*	33.91 *(37.43)*	36.23 *(31.12)*	47.39 *(46.20)*	150.39
Totals	60.10	63.13	52.50	77.92	253.65

Chi-square two-way contingency table showing observed and *(expected)* values for counts of unsafe gaps accepted as a function of geometry and age group, with a blocking passenger car and an opposing semi-tractor trailer traveling at 88 km/h.

	GEOMETRY				
DRIVER AGE	FULL POSITIVE	PARTIAL POSITIVE	ALIGNED	PARTIAL NEGATIVE	Total
25-45	22.22 *(20.86)*	24.09 *(21.47)*	19.19 *(19.93)*	21.36 *(24.61)*	86.87
65-74	15.56 *(14.78)*	14.80 *(15.21)*	12.00 *(14.12)*	19.20 *(17.44)*	61.56
75+	33.82 *(35.95)*	34.78 *(37.00)*	37.20 *(34.34)*	43.91 *(42.42)*	149.71
Totals	71.59	73.67	68.40	84.48	298.13

Chi-square two-way contingency table showing observed and *(expected)* values for counts of unsafe gaps accepted as a function of geometry and age group, with a blocking semi-tractor trailer and an opposing passenger car traveling at 56 km/h.

	GEOMETRY				
DRIVER AGE	FULL POSITIVE	PARTIAL POSITIVE	ALIGNED	PARTIAL NEGATIVE	Total
25-45	6.06 *(4.18)*	4.09 *(4.25)*	0.45 *(4.61)*	8.64 *(6.20)*	19.24
65-74	5.78 *(5.78)*	8.00 *(5.88)*	5.60 *(6.37)*	7.20 *(8.56)*	26.58
75+	44.93 *(46.81)*	45.65 *(47.61)*	56.52 *(51.60)*	68.26 *(69.34)*	215.36
Totals	56.77	57.74	62.57	84.09	261.18

Chi-square two-way contingency table showing observed and *(expected)* values for counts of unsafe gaps accepted as a function of geometry and age group, with a blocking semi-tractor trailer and an opposing passenger car traveling at 72 km/h.

	GEOMETRY				
DRIVER AGE	FULL POSITIVE	PARTIAL POSITIVE	ALIGNED	PARTIAL NEGATIVE	Total
25-45	14.14 *(13.41)*	19.09 *(15.74)*	9.09 *(14.38)*	23.64 *(22.44)*	65.96
65-74	12.00 *(11.06)*	12.00 *(12.98)*	8.80 *(11.86)*	21.60 *(18.50)*	54.40
75+	39.61 *(41.29)*	46.09 *(48.46)*	52.61 *(44.27)*	64.78 *(69.08)*	203.09
Totals	65.75	77.18	70.50	110.02	323.45

Chi-square two-way contingency table showing observed and *(expected)* values for counts of unsafe gaps accepted as a function of geometry and age group, with a blocking semi-tractor trailer and an opposing passenger car traveling at 88 km/h.

	GEOMETRY				
DRIVER AGE	FULL POSITIVE	PARTIAL POSITIVE	ALIGNED	PARTIAL NEGATIVE	Total
25-45	28.28 *(28.17)*	32.73 *(29.51)*	15.46 *(23.75)*	55.46 *(50.49)*	131.92
65-74	24.00 *(24.34)*	21.20 *(25.50)*	14.80 *(20.53)*	54.00 *(43.63)*	114.00
75+	44.44 *(44.21)*	47.39 *(46.31)*	51.30 *(37.28)*	63.91 *(79.25)*	207.05
Totals	96.73	101.32	81.56	173.37	452.97

Chi-square two-way contingency table showing observed and *(expected)* values for counts of unsafe gaps accepted as a function of geometry and age group, with a blocking semi-tractor trailer and an opposing semi-tractor trailer traveling at 56 km/h.

	GEOMETRY				
DRIVER AGE	FULL POSITIVE	PARTIAL POSITIVE	ALIGNED	PARTIAL NEGATIVE	Total
25-45	4.55 *(3.25)*	2.02 *(3.10)*	0.51 *(3.26)*	7.58 *(5.04)*	14.65
65-74	5.20 *(5.39)*	5.78 *(5.14)*	5.33 *(5.42)*	8.00 *(8.36)*	24.31
75+	46.09 *(47.19)*	45.41 *(44.97)*	50.24 *(47.40)*	71.01 *(73.19)*	212.75
Totals	55.83	53.21	56.08	86.59	251.71

Chi-square two-way contingency table showing observed and (*expected*) values for counts of unsafe gaps accepted as a function of geometry and age group, with a blocking semi-tractor trailer and an opposing semi-tractor trailer traveling at 72 km/h.

	GEOMETRY				
DRIVER AGE	FULL POSITIVE	PARTIAL POSITIVE	ALIGNED	PARTIAL NEGATIVE	Total
25-45	18.18 *(15.84)*	14.14 *(14.41)*	8.08 *(12.97)*	25.25 *(22.45)*	65.66
65-74	12.80 *(11.56)*	11.11 *(10.52)*	8.44 *(9.46)*	15.56 *(16.38)*	47.91
75+	43.48 *(47.07)*	42.51 *(42.84)*	44.44 *(38.54)*	64.73 *(66.72)*	195.17
Totals	74.46	67.76	60.97	105.54	308.74

Chi-square two-way contingency table showing observed and (*expected*) values for counts of unsafe gaps accepted as a function of geometry and age group, with a blocking semi-tractor trailer and an opposing semi-tractor trailer traveling at 88 km/h.

	GEOMETRY				
DRIVER AGE	FULL POSITIVE	PARTIAL POSITIVE	ALIGNED	PARTIAL NEGATIVE	Total
25-45	26.82 *(24.11)*	24.75 *(24.13)*	17.17 *(20.72)*	40.91 *(40.69)*	109.65
65-74	18.40 *(18.90)*	16.00 *(18.91)*	13.33 *(16.24)*	38.22 *(31.90)*	85.96
75+	40.87 *(43.08)*	45.41 *(43.12)*	43.48 *(37.02)*	66.18 *(72.72)*	195.94
Totals	86.09	86.16	73.98	145.32	391.54

APPENDIX C: FREE-RESPONSE DATA OBTAINED FOR THE LABORATORY STUDY OF ALTERNATIVE PEDESTRIAN CROSSWALK CONFIGURATIONS

Full Positive Geometry

Age	Comments on Intersection Features	Frequency
	Beneficial:	
25-45	DON'T WALK sign flashes long enough, gives enough time to cross.	4
	You have the island for safety.	3
	Length of time available is OK.	3
	Subject can walk fast, and the DON'T WALK sign is very long.	1
65-74	Enough time to cross.	3
	Feels that the island is safe.	1
	Right-hand side looks wider, but would still use it.	1
	Good visibility, central median.	1
	Could get to the island safely, but no farther.	1
75+	DON'T WALK sign (flashing) seems to give you more time than you would use.	5
	Enough time to reach the median.	3
	Could just make it across.	2
	Island makes it a little safer.	1
	Looks wide enough.	1
	Detrimental:	
25-45	Not enough time to cross.	4
	It would be safer if it had yellow poles.	3
	With the median, it makes the intersection appear longer.	1
	Median appears to be very far away.	1
	You could trip on the median if you weren't careful.	1
65-74	Subject does not like it without poles.	2
	You only have to cross half of the street, then you can wait for the cycle again.	1
	Feels as if she would only have enough time to reach the median.	1
	Not enough time.	1
	Island seems a little far away.	1
	Lanes look too wide.	1
	Too long of a walk if you have arthritis.	1
	Looks like an extra lane. Too far from curb.	1
	You may lose your balance if you were rushing across the intersection and tried to use the median.	1
	Distance between the curb and median is pretty far.	1
	Nothing to hold onto to get up to the median.	1
75+	Crosswalk cycle not long enough.	3
	Subject walks too slowly, would never make it to safety.	2
	It would take a little longer to reach the island.	1
	More territory to cross, so you will have to hurry.	1
	Median is too far away.	1

Partial Positive Geometry

Age	Comments on Intersection Features	Frequency
	Beneficial:	
25-45	Crosswalk cycle is sufficient.	3
	Island makes it safe.	2
	Would just make it to the other side/the landing helps a little.	1
	Doesn't look too wide.	1
	Can stop on the median.	1
	Looks safe, but you have to be careful of the median.	1
65-74	Enough time to cross.	5
	Island makes it feel safe.	2
	Good visibility, safe because no poles.	1
	Fairly safe.	1
	It has an island that you can wait on if necessary.	1
75+	Enough time to reach the median.	4
	This would be easy to cross, no problems.	3
	Seems to give you more time than you would use.	2
	Not quite sure of the length of the street, but subject feels that it looks safe.	1
	You have a long time to stand on the median and wait, so you are then prepared to walk.	1
	Median is close enough that, if needed, you could run to it.	1
	Detrimental:	
25-45	WALK sign is too short.	5
	Less time to cross.	2
	Seems too long to cross.	2
	No yellow posts make it a little unsafe.	2
	With the median, it makes the intersection appear longer.	1
	Too long to get from curb to island.	1
	At least three lanes of traffic make it look dangerous.	1
65-74	Island would be better if it had poles.	5
	Not enough time.	4
	Road looks too wide—not enough time to cross.	2
	Too long of a walk if you have arthritis.	1
	Subject does not like the idea of having the island in the way.	1
	You may lose your balance if you were rushing across the intersection and tried to use the median.	1
	No wheelchair ramps to step up and down.	1
75+	No posts make it unsafe.	2
	Subject walks too slowly for the time allotted.	2
	Too much up and down.	1
	To hard to cross if you have a cane.	1
	Looks unsafe.	1

Aligned Geometry, Double Median

Age	Comments on Intersection Features	Frequency
	Beneficial:	
25-45	Two islands make it very safe.	3
	Plenty of time to cross.	1
	Not too wide, and you could stop on either of the medians if needed.	1
	Crosswalk cycle is sufficient.	1
65-74	Very safe because there are two islands.	2
	Median strip is closer, plus you can stop twice.	1
	Extra island helps create more safe spots.	1
	Two median strips make it very safe.	1
	Enough time to cross.	1
	Two islands make it feel even safer (more places for safety).	1
75+	Crosswalk cycle is long enough.	6
	Two median strips make it safe.	4
	Could always use the median to wait for the light to change.	2
	You have a chance to stop on either of the islands.	1
	First island seems closer, making it safer.	1
	Very easy to cross.	1
	Detrimental:	
25-45	Two islands make it confusing.	3
	Too many islands.	2
	Two medians make it more hazardous.	2
	It seems as if it would take forever to cross the street.	1
	Street seems too wide.	1
	Too long to get from curb to island.	1
	Would only make it to the second landing, one curb is fine, but two make it harder.	1
	Not enough time to cross.	1
	Would prefer if the island had poles.	1
65-74	Too many lanes to watch.	3
	Two islands make it more difficult.	2
	Crosswalk time too short.	2
	Would only be able to reach the 1st island, would not be able to make it all the way across.	2
	It seems a little confusing with all of the islands. Someone may get hurt.	2
	More up and down walking, you could lose your balance.	2
	Would not like to be stuck on a median.	1
75+	Not enough time to cross.	2
	Subject walks too slowly for the time that it allows.	2
	Very confusing to pedestrians.	2
	This would be a hazard to pedestrians.	1
	Two lanes of traffic and a long walk make it dangerous.	1

Aligned Geometry, No Median

Age	Comments on Intersection Features	Frequency
	Beneficial:	
25-45	Easy, just straight across.	2
	Very simple intersection.	2
	No medians to get in the way.	2
	At least it is straight across the intersection and there are no obstacles in the way.	1
	Perception of the intersection is shorter since there are no median strips.	1
	Can be crossed quickly and only two lanes of traffic either way.	1
	This seems very easy since there is nothing blocking you.	1
65-74	It is a wide open area—pretty safe.	1
	Enough time to cross.	1
	She would use it because it is straight across.	1
	There is enough time to get all of the way across even without the median.	1
	Very easy, just walk across.	1
75+	Could just make it across.	1
	Nothing in your way to impede your walking.	1
	Detrimental:	
25-45	No median—very unsafe.	3
	No island for safety.	3
	No island to help you cross.	2
	WALK sign not long enough.	2
65-74	No island makes it hazardous.	8
	WALK phase is too short.	4
	Too much road and you may get hit.	3
	Too many lanes of traffic.	1
	Long (wide) lanes, subject would feel that she had to run across.	1
75+	Not enough time to cross.	9
	No median strip makes it dangerous.	4
	Subject walks too slowly for time allotted.	2
	Need a "safety" zone.	2
	Would never cross without a median.	1
	Very large intersection, not very safe.	1
	Since there is no median, you may get run over.	1

Partial Negative Geometry

Age	Comments on Intersection Features	Frequency
	Beneficial:	
25-45	If you can't make it all of the way across, you can use the median.	3
	Median makes it safe.	2
	It seems as if it is a shorter distance.	2
	Very simple intersection.	2
	It is not that long, and you can stop on the median if needed.	2
	Enough time to cross street.	1
65-74	There is enough time to reach the median.	4
	Short distance across, would not take long.	1
	Distance from the curb is closer.	1
75+	Subject would use the landing for safety.	3
	It gives you plenty of time to cross.	3
	No trouble in reaching the median.	1
	You could always make it to the median and then wait.	1
	The island is wide.	1
	Could just make it in the time allotted.	1
	Detrimental:	
25-45	Less time to cross.	2
	Would be better with poles.	2
	With the median, it makes the intersection appear longer.	1
	Not as safe, because there seems to be an extra lane.	1
	Does not like the fact that there are no poles. Feels that it is a very vulnerable intersection.	1
65-74	Too many lanes to cross over to the other side.	1
	Must walk up and down the median, not as easy as no median.	1
	Medians may not be the safest places—cars can hit you with or without poles.	1
	He does not like the idea of having the island in the way.	1
	No poles make it a little unsafe, you may lose your balance if you were rushing across the intersection and tried to use the median.	1
	No poles and she wouldn't be able to step up over the curb; the median would need a wheelchair ramp.	1
	It looks like a far walk to the island.	1
	Very dangerous, barely time to reach the island.	1
75+	Not enough time.	5
	Street appears to be too wide.	2
	Subject walks too slowly for the time allotted.	1

Full Positive Geometry With Median Delineator Poles (MDP)

Age	Comments on Intersection Features	Frequency
	Beneficial:	
25-45	Does not like the median strip very much.	1
	Yellow poles help make sure cars stay away from the median.	1
	She likes the yellow poles, they might stop a car from hitting her.	1
	Island makes it safe, the poles do not make a difference.	1
	Moderately safe—only one island.	1
	Barriers make it feel safe to stop on the median if you cannot make it all of the way across.	1
	Poles make it safer.	1
	Doubly safe—two medians, two poles.	1
65-74	Poles make it safe.	4
	Island makes it safe.	1
	Seemed relatively safe.	1
	Safer than others, enough time to reach the island.	1
	Since subject is in shape, she can use this and it would be safe.	1
75+	Enough time to reach the other side.	5
	Subject likes the poles/they make you feel safe.	2
	Safe, since you are very close to the median strip.	1
	Seems to give you more time than you would use.	1
	Island helps a lot.	1
	You can always wait in the middle if needed.	1
	Detrimental:	
25-45	Median does not allow strollers.	1
	Length of the crosswalk looks longer.	1
	Distance to the median has a higher potential for danger.	1
	Does not think that the poles make much of a difference.	1
	Wouldn't make it all of the way across.	1
65-74	WALK time is too short.	5
	Distance between the curb and the median is too far.	3
	Island is too far away.	2
	Poles are a distraction.	2
	Does not like the posts.	2
	Lanes look wider and more dangerous.	2
	Poles restrict visibility.	1
75+	Not enough time to cross (WALK sign is too short).	2
	Median is too far away.	1
	Subject walks a little slower, so this might be difficult.	1
	The first set of double lanes looks wider, and this makes it less safe.	1
	Seems like you may need to hurry.	1

Partial Positive Geometry With Median Delineator Poles (MDP)

Age	Comments on Intersection Features	Frequency
	Beneficial:	
25-45	Island makes it safe.	2
	Island with poles makes it safe. Far side only has two lanes.	1
	She likes the yellow poles, they might stop a car from hitting her.	1
	Enough time.	1
	Seems to be a short intersection.	1
65-74	Island seems safe due to the poles.	4
	Enough time to cross.	2
	Poles give it a feeling of safety.	2
	Likes the safety poles.	1
	Median acts as protection from oncoming cars.	1
	She would use it since it has poles.	1
	WALK sign seemed a little longer.	1
75+	Seems to give you more time than you would use.	2
	Subject would use the landing for safety.	1
	Median looks very safe.	1
	Might be able to go all of the way across.	1
	Likes having a place to stop half-way.	1
	Seems very safe.	1
	Pedestrian seems close to the median.	1
	Detrimental:	
25-45	Too many islands.	1
	It is OK, but not real safe.	1
	Median is not as close as before, but it has poles.	1
	It is too wide to get across for some people.	1
	Poles make it safer.	1
	Seems like enough time to cross.	1
	Median is too far away.	1
65-74	Distance to the island is very far.	3
	Doesn't seem very safe.	3
	Poles restrict visibility.	2
	Subject feels that the median could be considered an obstruction, and then it becomes dangerous.	1
	Poles may not make it as safe as it would appear.	1
75+	Not enough time.	3
	It would take longer to reach the island from the curb.	2
	Too much up and down.	2
	WALK sign is not long enough.	2
	Looks very dangerous.	1

Aligned Geometry, Double Median With Median Delineator Poles (MDP)

Age	Comments on Intersection Features	Frequency
	Beneficial:	
25-45	Two islands make it very safe.	3
	You can always use the island if you have to.	1
	Two medians to choose from, for different stopping points.	1
	Could have used a few more seconds on WALK and flashing DON'T WALK.	1
	Landing helps a little.	1
65-74	Poles make it safe.	3
	Extremely safe, two islands and double poles.	2
	It would be easy to reach the median.	2
	Enough time to reach safety.	1
	Safer than all of the others.	1
	Poles look sturdy.	1
75+	Poles make it feel safe.	3
	Very easy to cross.	2
	Enough time to reach either of the median strips.	2
	You could always wait on the median until the next cycle started.	2
	Subject would use one of the landings for safety.	1
	Very safe.	1
	Appears to be a little more time.	1
	Detrimental:	
25-45	It seems as if it would take forever to cross the street.	2
	Seems confusing.	1
	Not enough time on the walk signal.	1
	Too hard with two medians if you have young children with you.	1
	You have to stop twice to look both ways and it is very dangerous.	1
	Not nearly enough time to cross.	1
	Median is too far away to reach.	1
65-74	Extra lane of traffic makes it much more dangerous.	3
	A very long street to cross.	2
	Would not be able to step up and down.	2
	Subject does not like the poles.	1
	Subject is afraid of the two medians.	1
	Much more complicated intersection.	1
	Not enough time.	1
75+	Not enough time to cross.	3
	Medians are too far away.	2
	Too much up and down.	2
	Appears to be an extra lane, which makes it more dangerous.	1
	Subject walks too slowly for this intersection.	1

Partial Negative Geometry With Median Delineator Poles (MDP)

Age	Comments on Intersection Features	Frequency
	Beneficial:	
25-45	You have the island for safety.	3
	Less of a distance to cross.	2
	Median helps you walk across.	2
	Seems somewhat safe.	1
	It looks safe, but there is an extra lane to cross.	1
	Plenty of time to cross.	1
	Island, poles, enough time to cross.	1
	Seems to be a short intersection.	1
	Left-hand turn lane looks strange; it is average in safety, but nothing special.	1
	A little slower than the last one, but the landing helps a little.	1
65-74	Likes the medians with the poles.	4
	Plenty of time to cross.	3
	You can always wait on the island.	3
	Poles on the island, and the short distance makes it safe.	2
	Poles look sturdy.	1
	Poles help if a car would hit the median strip.	1
	Subject feels that the walk phase is sufficient.	1
	Median strip acts as protection from oncoming cars.	1
75+	Enough time to cross.	3
	You could use the median to wait until the light changed again.	2
	Median appears to be very close.	1
	Not quite sure of the length of the street, but it looks safe.	1
	Subject feels that he would be able to rush across.	1
	Median seems closer than before.	1
	Flashing DON'T WALK and WALK signs give you enough time.	1
	Detrimental:	
25-45	Takes too long to reach the median.	1
	Both signs were too short.	1
	WALK sign seemed to change faster than before.	1
65-74	WALK phase is too short.	1
	Subject does not like the poles.	1
	Poles give a pedestrian a false sense of security.	1
75+	Not enough time.	2
	Too much up and down.	2
	A long walk, for someone old.	1
	Seems dangerous, you must use caution.	1
	Barely enough time.	1

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