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Traffic Maneuver Problems of Older Drivers: Final Technical Report

Research and Development
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FOREWORD

This report presents the results of a multi-phased investigation aimed at better understanding difficulties encountered by older drivers on several common traffic maneuvers, as well as at evaluating tradeoffs of several simulation display methodologies. The study methods include a literature review, accident analysis, laboratory experimentation using three types of simulated displays, and a limited field validation. Several countermeasures are proposed to ameliorate the problems identified. This report will be of interest to researchers concerned with issues of older driver safety.

Copies of the report are being distributed to Federal Highway Administration Regional and Division offices and to each State highway agency. 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 the NTIS.

Lyle Saxton

Lyle Saxton, Director
Office of Safety and Traffic Operations
Research and Development

NOTICE

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16. Abstract

This project includes a literature review and accident analysis that supported the hypothesis that age differences in motion perception capabilities represent a likely source of difficulty for specific traffic maneuver problems experienced by older drivers. A feasibility study was performed to evaluate the most appropriate apparatus for use in later driving simulation tests planned in this research. Two sets of experiments were subsequently conducted. In the first experiment, drivers in three age groups--18-55, 56-74, and 75+ years of age--estimated the time-to-collision (TTC) of an approaching vehicle, from both stationary and moving perspectives. The conflict vehicle approached at varying speeds, and was removed from the view of the test subject at varying times/distances relative to the subject. In the second experiment, drivers viewed a dynamic roadway scene containing an approaching conflict vehicle. The subject's task was to judge the "last safe moment to proceed" with a particular traffic maneuver in relation to the conflict vehicle, to determine a gap judgment measure. Both the TTC and the gap judgment measures were obtained under laboratory conditions using multiple stimulus presentation methodologies in a driving simulator. Limited controlled field validation data were also obtained for both types of dependent measures, using the same test sample. Recommendations for countermeasures to accommodate older driver difficulties with turning maneuvers at intersections were developed consistent with the results of these studies.

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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	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	l
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
psi	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	ac
ha	hectares	2.47	acres	mi^2
km^2	square kilometers	0.386	square miles	
		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	megagrams	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	psi

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

(Revised August 1992)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

Table No. | Page

LIST OF TABLES (Continued)

Table No. Page

LIST OF TABLES (Continued)

LIST OF ACRONYMS

BAC . . . . blood alcohol content

CAV . . . . constant angular velocity

CLV . . . . constant linear velocity

CRT . . . . cathode ray tube

DC . . . . direct current

DMU . . . . distance measuring unit

FHWA . . . . Federal Highway Administration

GLM . . . . general linear model

HDTV . . . . high definition television

IDTV . . . . improved definition television

IVHS . . . . intelligent vehicle/highway system

NAB . . . . National Association of Broadcasters

NTSC . . . . National Television Standards Committee

PC . . . . personal computer

PennDOT . . . . Pennsylvania Department of Transportation

PROC-GLM . . . . general linear models procedure

RGB . . . . red green blue

RT . . . . reaction time

SAS . . . . Statistical Analysis System

SMPTE . . . . Society of Motion Picture and Television Engineers

TTC . . . . time-to-collision

WAIS-R . . . . Wechsler Adult Intelligence Scale (Revised)

INTRODUCTION

Increasing population in the U.S. will lead inevitably to increasing traffic densities and demand on highway facilities. At the same time, the proportion of highway users who are older drivers is dramatically increasing. Specific traffic maneuvers on differing classes of roadways appear to create special problems for older drivers, as evidenced both by over-involvement in selected accident categories and by self-reports from this user group. In particular, older drivers' difficulties with left turns against oncoming traffic, right turns into traffic, and highway crossing maneuvers on nonlimited-access facilities may be highlighted, as well as maneuvers on two-lane highways, including overtaking, passing, and car following. On freeways, entry/merging maneuvers, lane changing, and exit/weaving maneuvers also seem to pose exaggerated problems for older drivers.

This research supports the development of countermeasures to accommodate older drivers, based on investigations of perceptual judgments required to perform key driving tasks and a preliminary determination of more valid and reliable methods for obtaining measures of drivers' perceptual-cognitive response to the highway environment. Its overall goal is to improve safety and mobility for older drivers through environmental modifications that address the underlying reasons for driving maneuver difficulties.

PROJECT OBJECTIVES

The specific objectives of this project were: (1) to determine the limiting role of motion perception and gap judgment capabilities of older drivers in the performance of problem maneuvers; (2) to recommend highway engineering changes with the potential to ameliorate designated driving maneuver difficulties investigated in this research; and (3) to evaluate the suitability of different laboratory simulator display systems for non-interactive testing of driving performance capabilities relevant to this research topic.

The technical approach designed to meet these project objectives included the activities summarized below.

RESEARCH METHODS

The methods used in this investigation were: (1) a literature review to define the problem, based on an automated data base search plus ongoing work in the field; (2) an accident analysis of police-reported accidents in two States (Michigan and Pennsylvania), including driver age as a cross-tabulation variable; (3) laboratory measures of driver motion and gap judgment capabilities using three different simulator display technologies: large-screen video projection from laserdisc source, television monitor display from videodisc source, and large screen cinematic projection (35mm); (4) controlled field tests using the same measures obtained in the laboratory, for the same test sample; and (5) an engineering review of countermeasure options consistent with the driver performance differences found in the lab and field data collection efforts.

SUMMARY OF RESEARCH FINDINGS

The principal results of this work are summarized as follows:

- Prior research has indicated a significant age-related decline in the ability to detect the angular expansion cues presumed to be critical for accurate motion and gap judgments in traffic, and suggests that older drivers rely primarily or exclusively upon perceived distance to perform such judgments.

- Analyses of over 60,000 accident records in this project confirmed that turning and merging maneuvers are linked to the most exaggerated degrees of overinvolvement in multiple-vehicle accidents by older drivers.

- Evidence was **not** found to support the hypothesis that older drivers overestimate time-to-collision in their perceptions of the closing distance between themselves and another vehicle approaching either head-on or on an intersecting path, as a possible explanation of their overinvolvement in turning accidents.

- A relative insensitivity to approach (conflict) vehicle speed was shown for older vs. younger drivers, in that younger drivers adjusted their gap judgment of the "last safe moment to proceed" with a turn that took higher approach speeds into account, while older drivers as a group failed to allow a larger gap for a vehicle approaching at 60 mi/h (96 km/h) than for one approaching at 30 mi/h (48 km/h).

- A contradiction in the pattern of drivers' gap judgment responses to video stimuli in the laboratory vs. their responses to actual vehicle targets in the field was demonstrated in this research, whereas their pattern of responses to 35mm film stimuli was comparable to the field data. This finding supports a tentative conclusion that high resolution (high spatial frequency) cues showing correct size and perspective relationships of actual driving scenes are important elements for valid simulator measures of perceptual/cognitive performance.

RECOMMENDATIONS

As elaborated in the concluding section of this report, the principal recommendations of this project are as follows:

- In specific operating situations (such as intersections) where exaggerated accident rates for older drivers appear due at least in part to motion perception difficulties, this group could best be accommodated through highway information elements identifying conflict vehicles approaching at high speed and/or by highway engineering changes to reduce excessive speeds of through vehicles. A range of countermeasure alternatives are identified in the body of this report.

- While videodisc (laserdisc) technology provides an excellent image storage and playback medium for driving simulation applications from the standpoint of random access and experimental control, it is recommended that laboratory studies of driver perceptual judgments underlying maneuver decisions use stimulus presentation techniques affording higher image resolution than presently available through National Television Standards Committee (NTSC)-quality video signals.

BACKGROUND INFORMATION

REVIEW OF LITERATURE

Recent historical accident data, anecdotal evidence, and driver self-reports have suggested an exposure-corrected overrepresentation of older motorists for specific unsafe driving acts. There now exists a large body of evidence to document a decline with advancing age in sensory/perceptual (especially visual) skills, a range of cognitive functions, and the speed of psychomotor responses involved in driving.[1] The information presented in this section provides background for the hypothesis that age differences in motion perception can explain older driver overinvolvement in particular accident categories. On the basis of a review of laboratory tests of the perceptual skills of younger vs. older drivers, predictions concerning relative involvement rates among varying types of police-reported collisions in two States were developed and confirmed.

Age and Motion Perception/Gap Acceptance

Prior investigations have addressed motion perception abilities pertinent to driving, including time-to-collision (TTC) and gap-acceptance judgments, though only a subset has compared older and younger subjects. In TTC estimates, drivers estimate how long it takes, moving at a constant speed, to reach specified points in their path.[2] They are hypothesized to be based either on an "optic-flow" process, in which the driver's analysis of the relative expansion rate of an image (such as an oncoming vehicle) over time provides the estimate of TTC directly, or on a cognitive process in which TTC is estimated using speed and distance information.[3,4,5] In the first case, the driver relies on two-dimensional information--that is, angular separation cues (the image gets larger)--to estimate TTC; in the second, the driver calculates TTC on the basis of three-dimensional information. Several studies have supported the optic-flow model and the idea that two-dimensional, angular separation cues, separate from background information, suffice to allow drivers to estimate TTC.[5,6] As the simplest explanation of TTC estimation, this stance was adopted as a reasonable theoretical framework for the present study, though it is important to note that the work in this project was **not** designed specifically to verify one hypothesis versus another.

Relative to younger subjects, a decline (possibly exponential) for older subjects in the ability to detect angular movement has been reported. Using a simulated change in the separation of taillights, indicating the overtaking of a vehicle, a threshold elevation greater than 100 percent was shown for drivers 70-75 years of age vs. those 20-29 years of age for brief exposures at night.[7] 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, older persons required significantly longer to perceive that a vehicle was moving closer at constant speed: at 19 mi/h (30.6 km/h), decision times increased 0.5 s between ages 20-75.[8] The age effect was not significant when the vehicle was moving away from the subject.

Next, research has indicated that relative to younger subjects, older subjects underestimate approaching vehicle speeds.[9] Furthermore, analysis of judgments of the "last possible safe moment" to cross in front of an oncoming vehicle has shown that older persons (especially men) allowed the shortest time margins at 60-mi/h (96-km/h) approach speeds--older persons accepted a gap to cross at an average constant *distance* of slightly less than 500 ft (152.4 m), whereas younger men allowed a constant *time* gap and thus increased distance at higher speeds. These findings bear directly on the problem driving maneuvers investigated in this project.

Generally, there is an increased sensitivity across age groups to longitudinal vs. tangential movement. However, longitudinal movement is a greater problem for drivers because the same physical displacement of a vehicle has a much greater visual effect tangentially than longitudinally--that is, tangential movement results in greater relative motion.[10] Other findings relevant to motion perception and accident involvement, though undifferentiated by age in research to date, include the following:

- There appears to be general underestimation of TTC. As TTC increases, the error increases--in other words, as speeds go up, the error increases.[5]
- TTC estimates vary between experienced and inexperienced drivers. The former integrate time and distance to provide a safety margin, whereas inexperienced drivers use speed and distance perception alone.[6]
- Drivers have greater sensitivity to movement toward them than away, and there is high sensitivity to discriminating between directions of movement.[8,11] This implies that rear-end collisions more likely result from inattention and the inability to judge correctly the magnitude of relative motion, rather than from a limitation in detecting its direction. Drivers know when they are gaining on a car, but may be unaware of how fast.[12]
- An increase in the angular velocity is required for motion detection, with increasing separation between two objects.[11]
- Increases in the rate of conflict for merging maneuvers and conflict severity for turning maneuvers are related to increased variance in speeds in the traffic stream for which a driver is making gap-acceptance judgments.[13] That is, a principal source of risk at intersections is the error of a turning driver in judging gaps in front of fast vehicles.

Collectively, the motion perception literature implies that older drivers should have more difficulty than younger drivers with specific traffic maneuvers. Older drivers should have more accidents when: (1) turning left against oncoming traffic; (2) when simply crossing or turning into a traffic stream, although the differential should not be as high as for the first situation; and (3) where vehicle headways are important (e.g., in overtaking a lead vehicle).

Age and Accident Experience by Driving Maneuver: An Overview

A broad survey of findings published during the previous decade relating to trends in the accident experience of young and old drivers is summarized here. All implied comparisons are typically with the general population.

- California: Men and women drivers older than 70 years of age had significantly higher accident rates. Right-of-way violations were the leading cause of injury accidents and the primary collision factor in 30 percent of the fatal accidents in which older drivers were judged at fault.[14]
- United States (nationwide): Increased accident rates at signalized intersections following adoption of "right turn on red" are highest for drivers under 25 or over 55 years of age.[15]
- Toronto: A survey of motorists indicated that the frequency of collisions under peak-volume urban driving conditions on nonlimited-access roadways was reported to be highest for drivers under 21 and over 60 years of age.[16]

- Iowa: Higher rates were reported for the 65-70 age group, and even higher rates were reported for drivers 75 years of age and older. The highest percentages of older driver accidents were in the categories of failure to yield, improper turn, and failure to obey traffic signs. Twenty percent of accident-involved drivers over 75 years of age were attempting left-turn maneuvers when the collision occurred.[17]

- Great Britain (nationwide): Drivers ages 17-19 had the highest accident rates, although drivers ages 65 and older had roughly twice the expected number of accidents involving failure to obey intersection control and a far higher numbers of accidents involving turning across traffic.[18]

- New Brunswick: Analysis of 30,471 accidents during 10 yr showed that drivers ages 60 and older had accident rates equal to or worse than drivers under 25 years of age, and a higher at-fault rate. Specific problems were failure to yield and improper turning and reversing.[19]

This overview is a preliminary confirmation of the prediction that the relative accident involvement rates of older drivers can be ordered according to traffic maneuvers in which motion perception difficulties will most strongly influence their safety. The following rigorous analysis of accident data in two States, controlled for (induced) exposure and accident factors extraneous to driver age, further increases our understanding of these relationships.

OLDER DRIVER ACCIDENT INVOLVEMENT ANALYSES

Analyses of police-reported accidents in Michigan and Pennsylvania sought to focus on accidents in which drivers' motion perception was a significant contributing or causative factor. Accidents involving drinking drivers or vehicle equipment defects were excluded from consideration. Field reports that coded *driver 1* as the driver more at fault (or more causative of an accident) and *driver 2* as the one less at fault formed the basis for calculating relative involvement rates. This allowed the cross-tabulation of event frequencies as driver 1/driver 2 ratios by driver age group. The following four age groups were analyzed: 26 years of age and younger, 27-55, 56-75, and 76 years of age and older.

Michigan Accident Analysis

Michigan accident reports for 1986 through 1988 were examined. Accident report data were merged with other files to create records for analysis that contained entries describing the accident location (e.g., geometry), ambient environmental conditions, the crash occurrence and severity, driver and passenger(s) information (e.g., age and seat belt use), traffic citations associated with the event, and the vehicles involved and their drivers' intentions. Accident records associated with five specific maneuver types were examined: (1) merging and weaving maneuvers on limited-access highways, (2) lane change maneuvers on limited-access highways, (3) left turns against traffic, (4) crossing (gap-acceptance) maneuvers on nonlimited-access highways, and (5) overtaking and passing on two-lane, two-way rural roads. The accident records were analyzed in comparison with base conditions and defined by explicit variable limits.

Tables presenting complete driver 1-age by driver 2-age cross-tabulation data for the specified conditions referenced in this discussion have been deferred to appendix A. A summary table displaying driver 1/driver 2 ratios for each age group by maneuver is included below.

Table 1. Driver 1/driver 2 ratios by age group for each maneuver in Michigan accident data analysis.

Age group	Maneuver type				
	Merging on limited-access highway	Lane change on limited-access highway	Left turns at intersections[1]	Left turns at intersections[2]	Crossing highway at non-signalized locations
under 26	1.5	1.2	1.1	1.3	1.3
27-55	0.8	0.9	0.7	0.8	0.7
56-75	0.9	1.1	1.7	0.8	1.2
over 75	2.3	1.5	7.7	0.8	4.5

1 = Driver 1 turning left, driver 2 proceeding through intersection

2 = Driver 1 proceeding through intersection, driver 2 turning left

Merging and Weaving Maneuvers on Limited-Access Highways. Only accidents that occurred on or near ramps in the vicinity of intersections with the limited-access facility were considered in the analyses for this maneuver. Also, accidents were eliminated for situations in which it wasn't clear what maneuvers were occurring, such as when the vehicles were stopped or on the shoulder. Finally, driver intentions were considered. Valid intentions included going straight, passing, changing lanes, and starting up. Eliminated intentions included making a right turn and backing up. The resulting analysis set included 1,682 accidents.

The tables in appendix A present data in a matrix (cross-tabulation) of driver 1 age by driver 2 age for specified conditions. If driver 1 is at fault and driver 2 is the "innocent party" (i.e., driver 1 caused the accident and driver 2 just happened to be there), it is argued that driver 2 characteristics are implicit measures of exposure. Thus, the ratio of driver 1 to driver 2 characteristics is indicative of relative over or underrepresentation (marginal row proportions divided by marginal column proportions). For example, if the proportion of driver 1's 26 years of age and younger is greater than the proportion of driver 2's 26 years of age and younger, then this age group is overrepresented in accidents relative to their exposure. This approach is discussed elsewhere in the context of quasi-induced exposure.[20]

In general, the cross-tabulation data for this maneuver indicates that the ages 26 and younger group is overrepresented and the 27-55 and 56-75 age groups are underrepresented. The involvement ratios are 1.5, 0.8, and 0.9, respectively; and 2.3 for the oldest group. The small number of older drivers makes conclusions problematic, but the ratio is more than 1.0, indicating overinvolvement.

Of further interest is cross-tabulation of violations for driver 1 by age, which shows that different age groups committed different violations. Drivers 26 years of age and younger were far more likely to follow too closely and speed than drivers over 26 years of age. As older groups are examined, the tendencies shift: speeding becomes less likely, failing to yield more likely, improper use of lanes more likely, and following too closely less likely. Notwithstanding sample size, these trends carry over to the oldest driver group, which was least likely to speed and most likely to fail to yield and to use lanes improperly.

Drivers' accident experience in a given traffic situation (or for a given maneuver) on a given facility were also compared with their involvement levels in a superordinate "base" group of accidents encompassing either (1) all maneuvers/ situations on comparable facilities, **or** (2) the cumulative number of accidents involving a specific maneuver, across all facilities. For example, the base condition for rear-end accidents on limited-access highways could be **all** accidents on this type of facility **or** the number of rear-end accidents occurring on limited-access **and** nonlimited-access highways, whichever was of greater interest. Thus, merging and weaving accident totals were next compared with all accidents that occurred on limited-access highways. Interestingly, the two oldest groups accounted for proportionately more rear-end, merging, and weaving accidents than they did for all rear-end accidents occurring on limited-access highways (11.7 percent vs. 9.3 percent). Also, for driver 1's who were 26 years of age and younger, approximately 4.5 percent of all limited-access highway accidents were classified as merging and weaving accidents; for driver 1's who were 27-55 years of age, this number was approximately 4.9 percent; for driver 1's who were 56-75 years of age, approximately 4.8 percent were in this category; and for driver 1's who were 76 years of age and older, this number was 4.6 percent. In other words, merging and weaving accidents do not appear to be overrepresented in comparison with all accidents on limited-access highways, for any age group.

In summary, notwithstanding the small number of oldest drivers in this analysis set, drivers in different age groups appear to make somewhat different errors in merging and weaving accident situations: younger drivers are more likely to speed and follow too closely than older drivers, and older drivers are more likely to use lanes improperly and to fail to yield the right of way. Moreover, the shift from one violation to another appears to occur with increasing age. However, following too closely is still the most likely violation for all but the oldest drivers.

Drivers 26 years of age and younger and 76 years of age and older are overrepresented in merging and weaving accidents. Although generally underrepresented, the 56-75 age group is overrepresented during rush hours and dawn and dusk periods. There is some evidence to suggest that older drivers restrict their driving during poor weather: the magnitude of the involvement ratio remains about the same, but the percentage of older drivers involved as driver 1 and driver 2 decrease during adverse weather. There does not appear to be an interactive effect between merging and weaving and weather. Finally, this analysis indicated that older drivers appear to have more problems with trucks than with automobiles in merging and weaving situations.

<u>Lane Changes on Limited-Access Highways</u>. More than 13,600 accidents occurred away from interchanges, but it proved difficult to isolate those that were high speed lane-change accidents per se. Thus, all accidents occurring at operating speeds were considered relevant if the accident report specified the intention of changing lanes. An analysis set containing 10,398 records was thus defined.

The driver 1/driver 2 age matrix for this analysis indicates underrepresentation of drivers ages 27-55 and overrepresentation of the other three groups. An additional matrix for an accident subset in which driver 1 was attempting to pass yielded only 554 accidents, with several empty cells. Interestingly, the involvement ratio increased to 2.0 for younger drivers, but dropped to about 0.5 for the 56-75 age group. This may be because older drivers drive more slowly and attempt to pass less.

The distribution of violations by driver 1 age shows that relative to merging and weaving maneuvers, there is a higher proportion of speeding violations for all groups (as expected), lower failure-to-yield violations, and lower lane-usage violations. Following-too-closely violations are about the same. However, age group differences are greater for lane changing violations than for merging and weaving maneuver violations. More younger drivers are speeding here, fewer younger drivers have lane-usage violations (whereas there is a higher percentage for older drivers), and differences in following-too-closely violation rates by driver age are less pronounced for lane-change accidents.

Finally, when violation patterns for lane-change accidents on limited-access highways vs. the base condition (all accidents on limited-access highways) were examined and then compared with the earlier findings for merging and weaving maneuver accidents, a general shift in driver error was noted with increasing driver age. In maneuvers that involved a lane change, older drivers appeared to have more problems related to tracking and alignment of their vehicles. An alternative explanation for this is that older drivers simply do not drive as fast, so the percentage of involvement for lane-usage violations will increase. However, examination of the ratios of types of accidents to one another suggests that there is still some real shifting in the accident distributions that is not explained by older drivers' slower driving. For example, the ratio of following-too-closely to lane-usage accidents for the 26 and younger age group is about 2.7; for the 27-55 age group, 1.8; for the 56-75 age group, 1.2; and for the 76 and older age group, 0.7. This implies that different drivers are having problems apart from those caused by speed, although the trend is not as clear if the ratios between lane-usage and failure-to-yield accidents are considered.

As noted, the base-condition accidents were simply non-interchange accidents. For all driver 1 groups, the percentage of accidents accounted for by age group was about the same (less than 2 percent difference) for both lane-change-related accidents and the base-condition accidents (e.g., the 27-55 age group accounted for 52.4 percent of lane-change accidents and 50.7 percent of base accidents). Similar results were noted for the driver 2 group. However, it appears that the oldest group of drivers is generally underinvolved in this type of accident. This was determined by dividing the number of lane-change accidents on limited-access highways by the number of base accidents for each group. The results showed that for drivers 26 years of age and younger, 59.6 percent of all non-interchange accidents were defined as lane-change accidents; for drivers 27-55 years of age, 63.6 percent; for drivers 56-75 years of age, 59.2 percent; and for drivers 76 years of age and older, 50.0 percent.

Additional results from comparing lane-change accidents and base accidents include:

- Driver 1 violations for lane-change accidents were more likely to be improper lane usage (24.0 percent vs. 19.1 percent) or speeding (20.2 percent vs. 16.0 percent) and less likely to be failure to yield (2.3 percent vs. 5.2 percent) or following too closely (47.2 percent vs. 54.2 percent).

- Lane-change accidents are just as likely to occur during the non-rush hour period during the day, but more likely to occur during the non-rush hour period during the night (38.5 percent vs. 35.0 percent) and less likely to occur during rush hour (29.9 percent vs. 33.4 percent).

- Lane-change accidents were more likely to occur at night (72.7 percent vs. 66.5 percent), less likely to occur during daylight, and about just as likely to occur at dawn and dusk. Trucks were slightly more likely to be vehicle 2 in lane-change accidents vs. all accidents (20.4 percent vs. 18.5 percent), with a significant shift with driver 1 age (18.8 percent for 26 years of age and younger, 26.5 percent for 76 years of age and older).

In summary, because the lane-change maneuver on limited-access highways is hard to isolate, accidents that were clearly not lane changes were eliminated and the remainder were analyzed. Notwithstanding the small sample sizes for older drivers, findings and conclusions about lane changes on limited-access highways indicate that drivers in different age groups appear to make different errors when they are involved in accidents (younger drivers tend to speed and follow too closely, older drivers tend to use lanes improperly) and the shift from one violation to the other occurs with increasing age, but following too closely is still the most prevalent violation for all age groups but the oldest. Furthermore, across all age groups, speeding violations are more likely than merging and weaving accidents. Lane usage was less of a problem for the younger drivers than were merging and weaving accidents, but more of a problem for older drivers, as was following too closely. Failure to yield was not as much of a problem for any age group in lane-change accidents on limited-access highways.

Drivers 26 years of age and younger and 76 years of age and older appear to be overrepresented for lane-change accidents. Overrepresentation of drivers 26 years of age and younger is about the same as it is for merging and weaving accidents, but older groups appear to have fewer problems with lane-change accidents. Weather and time of day do not seem to have the impact on lane-change accidents that they do on merging and weaving accidents. Similar to merging and weaving accidents, older drivers appear to have more problems with trucks than younger drivers. However, when merging and weaving accidents were considered, there appeared to be a clearer trend with increasing age. With lane-change accidents there were only modest increases for the three youngest groups, and the oldest group had the most problems. However, all age groups have more involvement with trucks in lane-change situations than they do in general on limited-access roads.

Left Turns Against Traffic on Nonlimited-Access Highways. Given a large sample size, fairly specific accidents in this category can be identified by driver intention. That is, one of the two drivers in an accident was turning left. This resulted in an analysis set containing about 15,500 accidents where just more than 80 percent of the driver 1's were turning left. The distribution of combinations of driver 1 and driver 2 intentions were: (1) driver 1 was turning left and driver 2 was going straight (10,708), (2) driver 1 was going straight and driver 2 was turning left (1,863), (3) driver 1 was passing and driver 2 was turning left (about 600), and (4) both drivers were turning left (about 400). There was a scattering of other combinations. Analysis of only the first two, most frequent combinations in this list is reported. For the most part, signalized and unsignalized intersections were not separated because left turns against traffic involve the same judgment, regardless of whether the signal is green or simply not present. Almost 75 percent of the accidents occurred during the day, 20 percent occurred at night, and the rest occurred during dawn or dusk. About 70 percent occurred on dry pavement and more than 80 percent occurred during clear or cloudy conditions. About 56 percent occurred in urban areas. More than 80 percent of the vehicles involved were automobiles, and approximately 12 percent were trucks.

There were fundamental differences in the age distributions for drivers in the left-turn accidents. It may be recalled that for merging and weaving and lane-change accidents on limited-access highways, the driver 1 age distributions were roughly the same--from the youngest to oldest groups they were 38 percent, 50 to 52 percent, 8 to 9 percent, and 0.8 to 1.6 percent--the first two age groups account for more than 90 percent of the accidents. For left turns against traffic, these two groups account for less than 80 percent. Although it would appear that older drivers have substantially more problems with left turns than with merging and weaving and changing lanes, this factor may be tempered by exposure.

Examination of the driver 2 age distributions shows that they also were virtually the same for merging and weaving and lane-change accidents, but different for left-turn-against-traffic accidents. This is illustrated in the cross-tabulation data for this maneuver, when driver 1 is turning left and driver 2 is going straight. Relative to the maneuvers named previously, the percentages are higher for the 26 and younger age group, lower for the 27-55 age group, and similar for the two oldest groups. On the basis of involvement ratios, both groups of older drivers are greatly overinvolved; only the 27-55 age group is underinvolved. The net result shows that both groups of older drivers have a more serious problem with turning left than they do with merging and weaving and lane changing, whereas drivers 26 years of age and younger have less of a problem.

The cross-tabulation data for accidents in which driver 1 was going straight and driver 2 was turning left, shows that only drivers 26 years of age and younger appear to be over-involved. Older drivers do not appear to have a problem with drivers turning left across their paths. Of course, there is a substantial difference in what is required of a given driver in one situation compared to the other. When driver 1 is going straight and driver 2 is turning left, driver 1 is more likely to be moving and must first see the vehicle turning left across his or her path, and then decide whether to slow down or stop to allow the other motorist to cross. However, when making the left turn, driver 1 is likely to be stopped and must estimate time-to-collision, assess whether a gap in the stream exists, then accelerate and turn the vehicle. Both the driver's task loading and frame of reference change from one situation to the other.

When analysis of violation patterns indicated a driver 1 violation of failure-to-yield or improper turn (no signal), the proportional involvement rates were quite similar to those where driver 1 was turning left and driver 2 was going straight. This result indicates that these are high-incidence problems for the older groups. For other violations, older drivers had much lower relative-involvement ratios, though sample sizes were small.

During the non-rush hour day period, the two older groups were overrepresented. The 76 and older age group had a ratio of more than 6.0, and the 26 and younger age group had an involvement ratio that was just more than 1.0. There was, in essence, a trade-off between these two groups for the rush hour and non-rush hour night periods. For the latter, the ratio of the 26 and younger age group had increased to about 1.2 and the 76 and older age group had decreased to 3.8. The involvement ratios for the two middle groups were roughly the same, regardless of time of day; the 27-55 age group was underinvolved and the 56-75 age group was overinvolved. The older groups were always overinvolved in left-turn accidents, and the 76 and older age group always had significantly more overinvolvement (especially during the day), with its worst problems occurring during non-rush hour day periods. Finally, bad weather and darkness decreased the degree of overinvolvement for drivers 76 years of age and older; involvement ratios were clearly higher for better environmental conditions. Also, older drivers' problems with trucks were not noted here.

A comparison of the left-turn-against-traffic accidents with all multiple-vehicle accidents on U.S. and State numbered routes (including limited-access highways) was conducted as the base-condition comparison. Overall, left-turn-against-traffic accidents accounted for 6.5 percent of the base-condition accidents for drivers 26 years of age and younger, 6.0 percent for drivers in the 27-55 age group, 8.9 percent for drivers in the 56-75 age group, and 11.9 percent for drivers 76 years of age and older. Although this comparison is based on frequencies, it seems apparent that left-turn-against-traffic accidents are increasingly likely for older drivers.

Summarizing for other variables, the occurrence of left-turn-against-traffic accidents was more likely than base-condition accidents during daytime periods (30 percent vs. 20 percent) and during good weather (by about 5 percent), was equally likely in urban areas (56 percent), and was somewhat less likely to involve trucks as either vehicle 1 or vehicle 2.

It must be reiterated that the accidents used for left-turn-against-traffic accident analysis were specifically selected by accident type and driver intention. In general, there was no differentiation made between signalized and nonsignalized intersections or by the number of lanes present. Nevertheless, older drivers evidenced serious problems making left-turn maneuvers against oncoming traffic. Conversely, older drivers confronted with a left-turning vehicle appeared to have no special problem. Interestingly, adverse environmental conditions did not demonstrate a deleterious effect in the involvement of the older driver in left-turn-against-traffic-type accidents.

Crossing-Gap-Acceptance Maneuvers on Nonlimited-Access Highways. For this maneuver, different types of crossing maneuvers were separated. Thus, nonsignalized intersections were isolated and mid-block, nonintersection accidents were not considered.

The difference between the two types of gap-acceptance maneuvers (left turn against traffic and crossing gap acceptance) was of central interest in this analysis. This was examined by first investigating the differences between driver 1 violations by age. For crossing-gap-acceptance accidents, 90 to 95 percent of all violations were for failure to yield the right-of-way, compared to 70 to 75 percent for left-turn-against-traffic accidents. Most of the shift, however, was due to citations for improper signaling of a turn. This was cited for 20 to 25 percent of the left-turn-against-traffic accidents, but for less than 4 percent of the crossing-gap-acceptance accidents. For crossing-gap-acceptance accidents, it was fairly clear that the citations for failure to yield steadily increased with driver age, albeit over a fairly narrow range.

For time of day, the pattern was basically the same as reported earlier: there were differences between the two maneuvers, but the magnitudes and directions of difference were about the same. This leads to the conclusion that there is little difference by time of day. For road surface condition, the results were somewhat different: on dry roads, younger drivers were slightly more likely to be cited for failing to yield but there was little change for older drivers, and on roads that weren't dry, younger drivers shifted toward more speeding citations for crossing-gap-acceptance accidents but there was little change for older drivers.

Comparing results for left-turn-against-traffic accidents and crossing-gap-acceptance accidents highlights some important differences. The involvement ratios for the left-turn accidents (1.1, 0.7, 1.7, and 8.0 for youngest to oldest age groups) are comparable to those for crossing, which are 1.3, 0.7, 1.2, and 4.6. There is minor unexpected variation in the driver 2 age distributions: the left-turn maneuver accounts for a higher proportion of the accidents than the crossing maneuver, so turning left across traffic is a more serious problem for the older driver. This may result from the contexts in which the driver of the turning and crossing vehicle must perceive and react to the other vehicles: for left turns across traffic, the conflicting vehicle is coming straight toward the turning driver, who must estimate time-to-collision with the oncoming vehicle or perceive an acceptable gap between oncoming vehicles; and for crossing maneuvers, the other vehicle is coming from the side. Although similar judgments must be made in these situations, the view to the approaching vehicles is different, and angular movement is easier to detect in the latter case.

Examination of the vehicles encountered by the crossing driver revealed a slight tendency for drivers 76 years of age and older to have more difficulties with trucks than with automobiles. The truck percentage (as vehicle 2) was approximately two points higher than for any other age group (15.6 percent vs. 13.1 to 13.8 percent).

Overall, crossing-gap-acceptance accidents account for 3.1 percent of base-condition accidents for drivers 26 years of age and younger, 2.9 percent for drivers in the 27-55 age group, 4.6 percent for drivers ages 56-75, and 7.4 percent for drivers 76 years of age and older. Though crossing accidents appear to account for a high percentage of all the accidents of older drivers, overinvolvement does not appear to be as great as it is for left-turn-against-traffic accidents.

A simple comparison of the percentage of accidents that each age group accounts for also shows that the representation of the two youngest groups is lower for crossing-gap-acceptance accidents than for the base condition (41.6 vs. 44.2 percent for the 26 and younger age group and 35.8 vs. 41.2 percent for ages 27-55) and higher for the two oldest groups (15.7 vs. 11.4 percent for ages 56-75, and 6.9 vs. 3.1 percent for ages 76 and older). These percentages are very similar to those for left-turn-against-traffic accidents--about a point lower for the three youngest age groups and somewhat higher for the 76 and older age group. For the driver 2 age distributions, there are only modest differences (less than 2 percent) between the two maneuvers. In general, the involvement ratios are lower for the two younger groups and higher for the two older groups when crossing-gap-acceptance accidents are compared with the base condition. Compared with left-turn-against-traffic accidents, the involvement ratios for crossing-gap-acceptance accidents are higher for drivers ages 26 and younger and ages 56-75, and lower for the other two groups.

Comparisons between the crossing-gap-acceptance accidents and the base condition for other factors showed:

- About 26 percent of the intersection accidents and approximately 30 percent of the base accidents occurred during non-rush hour night periods.

- Similar percentages of accidents occurred during clear or cloudy conditions (81.5 percent for crossing gap acceptance and 78 percent for the base condition).

- Dry pavement accounted for 70 percent of the crossing-gap-acceptance accidents and 65 percent of base-condition accidents.

- A somewhat higher percentage (52 percent) were rural accidents, compared to the base condition, in which the percentage was approximately 44 percent.

- Cars accounted for just over 76 percent of the vehicle 1's and about 82 percent of the vehicle 2's in base-condition accidents compared to crossing-gap-acceptance accidents, where 83 to 84 percent of both vehicle 1's and vehicle 2's were cars.

- Trucks accounted for almost 17 percent of base-condition vehicle 1's and 15 percent of base-condition vehicle 2's, vs. 13 to 14 percent for crossing-gap-acceptance accidents. Overall, the crossing-gap-acceptance accidents (relative to base-condition accidents) tended to be more likely to occur during daytime periods, under good weather conditions, and in rural areas, and were less likely to involve trucks.

In summary, comparison of the involvement of different age groups of drivers in different types of gap-acceptance accidents showed that the older drivers are relatively overinvolved in both left-turn-against-traffic and crossing-gap-acceptance accidents. However, left turns across traffic appear to present more of a problem for drivers 76 years of age and older than crossing or turning into traffic.

The principal violation for all groups, but increasing with age in absolute terms, is failure to yield the right-of-way. There is not, however, the clear shift from one violation to another, as was apparent for the maneuvers on limited-access roads. Time of day appeared to have little importance in explaining differences between age groups, although road surface condition appeared related to an increased likelihood that younger drivers would be speeding. Explicit comparison of driver age group involvement in crossing vs. left-turn accidents at unsignalized intersections showed that older drivers had more severe problems with turning left across traffic than with crossing the traffic stream. However, this does not mean that they have no problem with crossing maneuvers; they clearly have problems with both. Other factors that might make crossing gap acceptance more or less difficult were also examined: there appeared to be a volume-related effect, although it was not consistent. There also appeared to be a greater problem for the oldest group when interacting with trucks.

Overtaking and Passing on Two-Lane, Two-Way Rural Roads. A severe problem with sample size was encountered after the stratifications had been made to clearly define passing accidents. It appears highly likely that there are more passing-related accidents than were isolated, but it is not clear how they can be identified. Of the more than 230,000 accidents originally identified as meeting initial criteria, only 2.2 percent (fewer than 5,100) were identified in which driver 1 intended to pass; after controlling for road type, fewer than 200 remained.

Distributions of driver 1 age (by intention) show that for the base group, approximately 3.1 percent of the drivers are in the 76 and older age group vs. only 1.9 percent whose intention was to pass on a two-way, two-lane rural road (similar results were noted for the 56-75 age group). This is probably indicative of the fact that older drivers drive more slowly and are less likely to overtake vehicles.

Single-vehicle accidents were also investigated, specifically, those in which the driver's intention was to pass. Sample sizes were small, but it was again clear that accidents in which the intention of driver 1 was to pass had a far higher representation of drivers 26 years of age and younger than any other. The sample was not stratified (e.g., urban vs. rural) because of its small size.

In summary, similar to the results for passing and overtaking maneuvers on limited-access highways, younger drivers appear to be overrepresented in these accidents. This is consistent with a distribution of driver speeds that has drivers 26 years of age and younger traveling the fastest, and average speeds decreasing by age. This would have the effect of the youngest drivers overtaking and passing drivers far more often than the oldest driver, who, generally speaking, would overtake very few drivers. Because of extreme problems in isolating accidents that clearly involved overtaking and passing maneuvers on two-lane, two-way rural highways, it was impossible to come to any definitive conclusion about problems common to the older driver.

General Trends in Michigan Accident Data Analysis. Overarching trends emerging from the analysis of Michigan accident data files included the following:

- A pronounced overinvolvement by older driver 1's as the most-at-fault motorist in turning accidents was limited to situations where the older motorist was the turning driver--when the through driver in the same situation was shown to be most at fault on the police report, only the **youngest** motorists were overinvolved.

- Accident overinvolvement for older drivers was most pronounced when the least amount of angular expansion information for gap judgment was available, i.e., when driver 2's vehicle was approaching head-on; older driver relative involvement rates were more modestly inflated when the other vehicle approached from the side, and were not at all inflated when the other vehicle turned across the older driver's path.

- Violation data for accident-involved drivers deemed most at fault showed contrasting patterns by age--younger drivers were far more likely to speed and follow too closely, while older drivers most often caused accidents by failing to yield right-of-way and by improper lane usage.

Pennsylvania Accident Analysis

Police-reported fatal accident records for the period of 1977 to 1986 and nonfatal multiple-vehicle accident records from 1984 to 1986 in the Pennsylvania Department of Transportation (PennDOT) data bases served as the basis for a parallel analysis in search of convergent evidence for the accident-involvement patterns documented for Michigan drivers. These incidents were screened to remove cases in which the most-at-fault driver was known to have a blood alcohol content (BAC) of at least 0.10 percent or to have refused a breath test. This was done to focus analyses on driver judgment errors separate from the effects of intoxication. A total of 12,159 records were eligible for analysis under this criterion.

Calculations of relative accident involvement by the same four age groups of drivers examined in the Michigan analysis were performed, reflecting ratios of accident frequency counts for each group in which a group member was the most-at-fault driver (driver 1) in the incident and those in which group members were the other involved operator (driver 2, or the "victim"). For example, with respect to the overall accident record data base of 12,159 cases, drivers 26 years of age and younger demonstrated a ratio of driver 1 vs. driver 2 frequency counts of 4,903 to 3,833, or an overinvolvement rate of 28 percent. By comparison, the 27-55 age group was underinvolved by 19 percent, and the 56-75 age group was split nearly evenly with driver 1 and driver 2 frequencies of 1,722 and 1,742, respectively. For drivers 76 years of age and older, 341 driver 1 cases and 168 driver 2 cases on these accident reports described an overinvolvement exceeding 50 percent.

The same cross-tabulation analysis approach was applied to relevant fields in the Pennsylvania accident records denoting sets of "vehicle movement" and "operator performance failure," contributing factors in each accident occurrence. The relative involvement rates by driver age group for accidents represented by vehicle movement categories of interest are shown in figure 1, also including the "all accidents" trend described above. In figure 2, relative accident involvement by age group for a range of pertinent operator performance failure factors is presented.

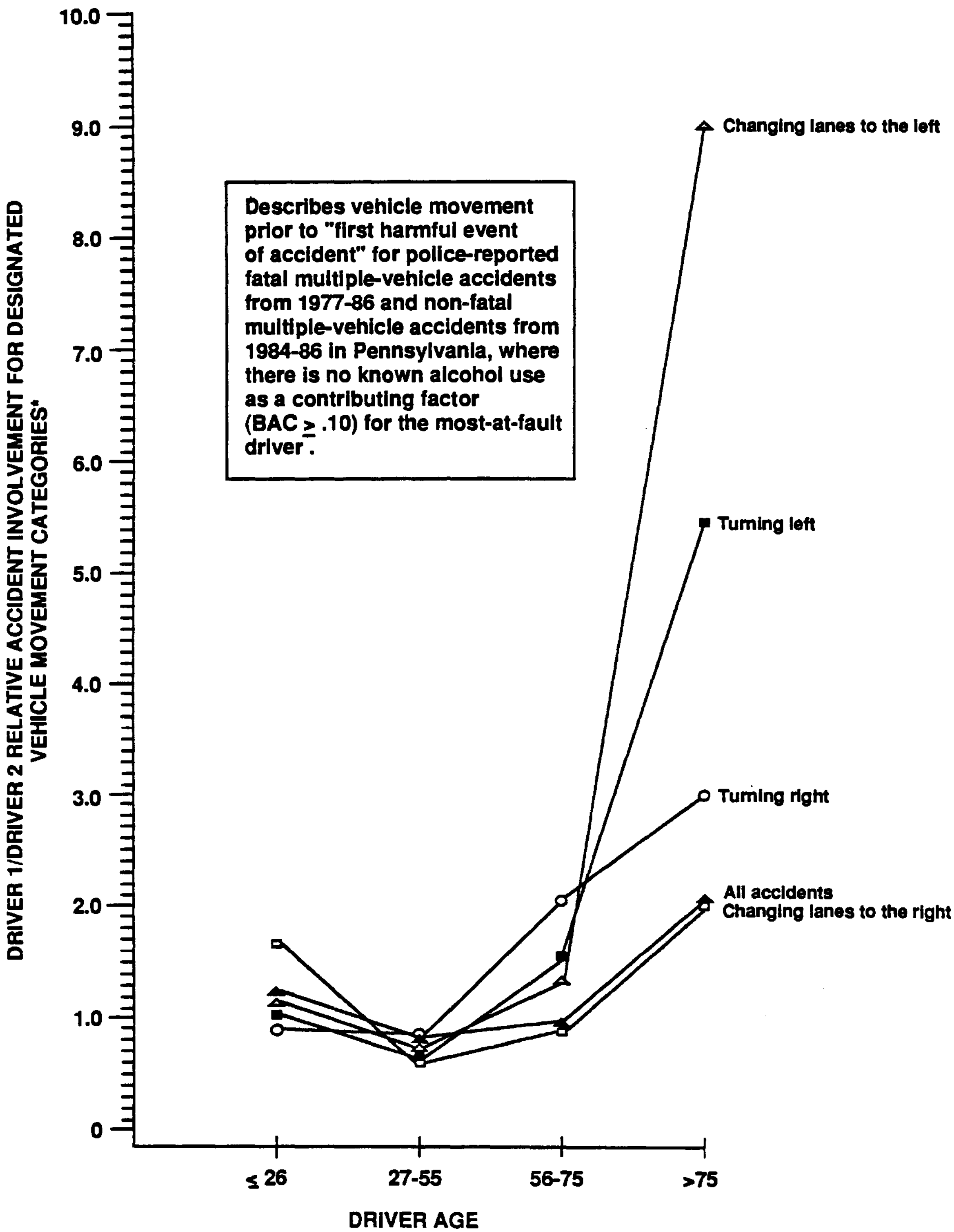
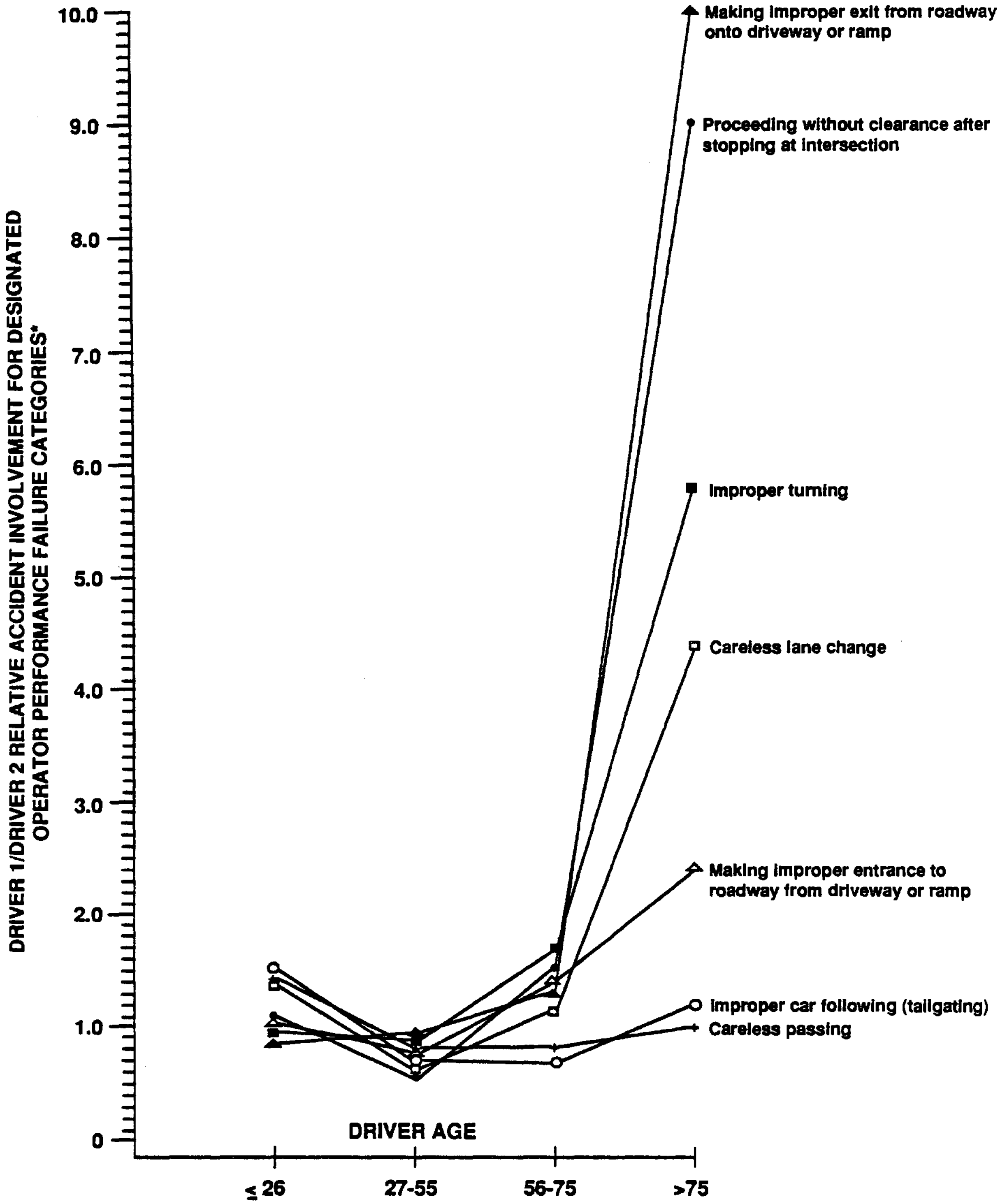


Figure 1. Relative accident involvement by driver age according to specified vehicle movement categories.



*For police-reported fatal multiple-vehicle accidents from 1977-86 and non-fatal multiple-vehicle accidents from 1984-86 in Pennsylvania, where there is no known alcohol use as a contributing factor (BAC ≥ .10) for the most-at-fault driver.

Figure 2. Relative accident involvement by driver age according to specified operator performance failure categories.

The results displayed in figure 1 demonstrate overinvolvement by drivers 26 years of age and younger, not only for all accidents examined, but also for incidents in which the vehicle movement before the "first harmful event of the accident" was described as turning left, changing lanes to the left, and changing lanes to the right, in increasing order of relative (driver 1 vs. driver 2) involvement. As noted above, drivers ages 27-55 were proportionately underinvolved with respect to all vehicle movements considered. For the 56-75 age group, there was no indicated overinvolvement for the changing-lanes-to-the-right category, but relatively higher driver 1 frequencies were shown for accidents in which the vehicle movement was changing lanes to the left, turning left, and turning right. The most consistent and extreme overrepresentation in driver 1 counts was noted for drivers 76 years of age and older; turning left and changing lanes to the left were identified as the most problematic vehicle movements.

In figure 2, age-related trends are shown for the frequency of involvement in accidents as the most-at-fault operator for whom a contributing factor was noted by police in one of seven categories (improper exit from roadway onto driveway or ramp, proceeding without clearance after stopping at intersection, improper turning, careless lane change, improper entrance to roadway from driveway or ramp, improper car-following (tailgating), and careless passing) against the frequency of being identified as driver 2 in such incidents. Considerable similarity to the results presented in figure 1 is apparent. The 26 and younger age group is marginally underinvolved in improper entrance to and exit from the roadway as well as improper turning, and it is overinvolved in all other operator performance failure categories. Drivers ages 27-55 are either proportionately represented or underrepresented as driver 1 in all measures. Tailgating and careless-passing relative involvement rates remain low for drivers ages 56-75, but overinvolvement in all other performance failure categories is indicated, with improper turning being the most prominent error. For drivers 76 years of age and older, only the careless-passing relative involvement rate showed an underrepresentation for performance error; a modest increase in the driver 1/driver 2 ratio for tailgating and sharp to dramatic increases for all other problem behavior categories were shown for this group.

In summary, examination of traffic-accident experience by driver age generally verified predictions of age-related overinvolvement in specific types of traffic accidents. The difference in magnitude was not explicitly compared, but the ordering of the seriousness of the problem (by age) showed some general agreement. For example, where prior research suggested that older drivers would have problems judging left-turn and crossing maneuvers, the accident analysis showed the same results in the same order. The ordering (left-turns being worse than crossing) was expected on the basis of the relative difficulties with longitudinal vs. tangential judgment of motion in the laboratory.

Left turns are clearly the most serious problem: older drivers have problems judging time-to-collision and acceptable gaps, and these problems are exacerbated by older drivers' generally slower response rates. When the highway environment is degraded, older drivers' experiences make them more cautious, which results in safer outcomes. With crossing maneuvers, older drivers have the same types of judgmental problems, but they are somewhat less severe because of the increased ease of successfully judging vehicle motion. Furthermore, the slower physical response is a little less critical because the crossing maneuver takes less time to clear the path of an oncoming vehicle than the left-turn maneuver.

The problems older drivers were expected to have with overtaking and passing were not as clearly identified in the field data; this was arguably because of the older drivers' lower operating speeds and consequently, fewer instances of overtaking other vehicles. Thus, though older drivers may have more serious problems than younger drivers in judging following distances, they simply overtake other vehicles much less often. As the proportion of older drivers in the population increases however, the situation in which a slower lead vehicle and an overtaking vehicle both are operated by an older driver is likely to rise, and an increasing frequency of older driver 1's in these accidents may be observed.

FEASIBILITY OF LABORATORY METHODOLOGY

This project task examined technical and cost information for varying approaches to present test stimuli and record subjects' responses in the planned motion judgment and gap acceptance laboratory studies. This section of the final report summarizes strengths and weaknesses of alternative simulator system elements including: (1) the projection surfaces (screens), (2) the image storage medium, (3) the image recording format, (4) the choice of camera lens for image recording, (5) hardware for image display and image enhancement, and (6) system interfaces with driver performance data collection instrumentation. At the conclusion of this section, a description of the physical layout of the laboratory simulator system designed to address the present data collection needs is presented.

SIMULATOR PROJECTION SCREENS

A goal in the design of the laboratory driving simulator for this research was to provide a total field of view of 180° or more to a subject. The choice of surfaces on which to project the driving test scenes considered both curved and flat screens to meet this design requirement. Other screen parameters evaluated in this task included the type of support structure (rigid mount vs. flexible/freestanding), gain factor, and ambient light rejection properties.

A high-end option currently used in a simulator system in the automobile industry was first considered due to the superior image quality it could afford. This curved screen design--actually a compound surface resembling a section of a torus--offered high luminance efficiency, uniform light return, seamless construction, high gain (up to 4:1), and excellent rejection of stray light that can mask the projected image. As a freestanding system with a self-adjusting framework of tuned aluminum members, this design reputedly eliminates sag and saddle in the screen that can distort the projected image. A screen design appropriate to the needs of this project was prepared by the manufacturer; the figure quoted was in excess of $70,000, however, and for this reason was rejected as a feasible option for the present laboratory studies.

Other curved screen designs were reviewed and found to be unsatisfactory, due to a combination of cost and performance factors. Image quality drops significantly relative to the high-end product described above, and special lenses were typically called for to achieve a projected image that was simultaneously in-focus and of the same brightness at the center vs. the edges of the screen. Also, curved screens placed serious restrictions on the feasibility of using rear projection techniques, which had been previously identified as a preferred approach for this work.

Flat projection screens were thus identified as the best choice for achieving acceptable levels of image brightness, using "off-the-shelf" projection hardware and lenses, at a cost within the present project budget. Specifically, rear-projection screens, at a unit cost of approximately $3,300, were subsequently identified as the best choice for the planned laboratory studies. The selected screen was a freestanding design with a tubular aluminum frame. Its gain factor was rated at 1.8, indicating that approximately 88 percent of the light incident upon the screen is visible to the viewer on the other side, assuming standardized relationships governing the placement of the projector for a screen of a given size and shape (i.e., aspect ratio).

This particular product was neutral in color and of very fine grain, making high resolution of image details possible. Key assumptions regarding its appropriateness for this project were darkness behind the screen, except for the image source, and low ambient light in the laboratory environment. Both of these conditions were met in the motion judgment and gap acceptance laboratory test methodologies, as described later in this report.

IMAGE STORAGE MEDIUM

The options considered in this task for storage of the driving scene test stimuli to be used during laboratory data collection included film, videotape, and optical laserdisc. Performance criteria determining the best choice(s) for the planned simulation were: (1) provision of high image resolution (definition), (2) no image degradation after repeated presentations, and (3) an ability to rapidly and randomly access any given driving scene, to permit the widest possible control over the ordering of test trials during stimulus presentation.

According to these criteria, videotape was identified as the least satisfactory option, with film and laserdisc both possessing relative strengths. A cinematic medium permits storage of the highest resolution image, but this medium is brittle. Its durability over repeated presentations was questionable, and randomization of scenes across trials or trial blocks, while possible with multiple reels and creative splicing of frame sequences, is time-consuming and physically cumbersome to perform in the laboratory. Laserdisc image storage, by comparison, allows random access of driving scenes/trials, and the image suffers no discernible degradation over repeated presentations. Resolution on laserdisc can approach that of film, using high-bandwidth signals in the high definition television (HDTV) format, though this is achieved only at considerable expense. At the time this task was performed, a single HDTV disc-pressing cost $10,000 to $12,000. A conventional National Television Standards Committee (NTSC) video signal laserdisc can be pressed for a cost of under $500, but image resolution is noticeably inferior, particularly when magnified for large-screen projection.

As a common denominator to describe relative resolution of these image storage media, a conventional NTSC laserdisc has a practical upper limit of about 400 horizontal lines of information storage per video frame after signal processing onto the disc, and is commonly characterized by resolution in the 260- to 300-line range as per current broadcasting standards. An HDTV disc can accommodate 1,125 lines of information per frame, and the equivalent resolution of cinematic media approaches the 100 lines per millimeter designation of the filmtrack (e.g., 16mm preserves the equivalent of 1,200 to 1,600 lines of information, 35mm preserves 3,000 to 3,500 lines, etc.).

A remaining factor in evaluating laserdisc options was the choice of constant linear velocity (CLV) vs. constant angular velocity (CAV) information storage formats. CAV discs always spin at the same rate (1,800 r/min) and show one frame per revolution; CLV discs turn at a variable rate--more slowly toward the outer end of the spiral track and more rapidly toward the inner end--so that the relative velocity between the laser focus and the disc remains constant. The CAV format offers individually addressable frames and much higher quality variable playback speed display capability (including freeze frame), plus quicker transport times from one address to another. In fact, smooth transitions in playback speed resulting in apparent acceleration or deceleration of the simulator vehicle are easily achieved with the CAV format. However, CLV discs offer higher storage capacity as each side of a CLV discs holds twice the information that can be stored on a CAV disc.

As described in the later explanation of the research design for the motion judgment and gap acceptance laboratory studies, both cinematic and laserdisc media were judged as feasible for storage of driving scene images in this project. Further, subjects' responses to the same stimuli, using one medium in comparison to another, provided valuable data concerning systematic biases that may be introduced as a function of a designated display technique for driving simulation.

IMAGE RECORDING FORMAT

Consistent with the preceding material, both video and cinematic techniques offered viable alternatives for the recording of real-world (controlled) driving images to use as test stimuli in this research. A critical analysis in this task focused upon the desire to retain as much visual detail as possible in each frame, according to the hypothesis that time-to-collision and gap judgments depend at least in part on drivers' processing of angular expansion cues of a vehicle target, which in turn will inevitably be impaired through loss of high frequency spatial information. As discussed in greater detail below, the presentation of a correct-perspective image to subjects in the driving simulator also required a large screen, resulting in significant image magnification relative to its size at the time of recording. Together, these considerations pointed toward image resolution as the key factor in selecting an optimal recording format.

A test viewing of outdoor scenes recorded using conventional (NTSC) video technology, including S-VHS and Beta SP formats, demonstrated a degree of image definition on an 8-ft (2.4-m) screen that was judged to be of marginal-to-poor quality with respect to the driver perception tasks in this research. With an even larger screen size later defined as most appropriate for the laboratory data collection needs, further image degradation would result. In particular, individual scan lines became visible at this degree of image magnification, with a resulting fuzziness that obscured the high frequency cues believed to be crucial to the present measures of driver performance. Costs for NTSC video recording, including camera rental, tape stock, and the services of a camera operator, can be held to less than $500/d on location.

A similar test viewing of an HDTV image, presented in a studio setting on a 10-ft (3.1-m) screen, revealed a startling gain in image resolution. From a viewing distance representative of a subject's eye-to-screen distance in the laboratory, no discontinuities in the HDTV image were visible; the amount of detail for distant scene elements was clearly superior to the NTSC image, with minimal dropout of high spatial frequency or "edge" information. Costs for filming in HDTV in 1991 ranged between $7,500 and $10,000 per camera per day. While this cost was expected to drop significantly, even during the period of performance of this project, it should be noted that filming with three cameras was planned to record the overall field of view desired in the driving simulator. Again, project budget constraints ruled out the use of HDTV as the recording format for driving scene test stimuli.

The remaining broad set of options for stimulus recording was cinematic filming. This set of options differed in terms of the size of the negative--16mm, 35mm, or 65mm. Each of these progressively larger film negative sizes results in a sharper image for a screen of a given size, since the greatest perceived image quality results with relatively smaller degrees of image magnification. (The grain size is equal on film for all negative sizes; more grain is used to record the image with larger negatives.) As the image size is multiplied to magnify its size from that recorded on the negative to that desired for viewing, more information is preserved on larger negatives for any unit area of the projected image. Of course, the cost of filming also increases from 16mm to 35mm, and by an even greater amount from 35mm to 65mm. Including camera rental, film stock, the camera operator, and sound recording, a representative cost for 16mm filming is $1,000 per camera per day. This figure increases by approximately 50 percent for 35mm filming and by 150 percent for 65mm. Disregarding other factors, the largest possible negative size was most desirable for the filming of stimulus scenes in this research.

Other important issues related to cinematic approaches for the recording of test stimuli were the required production efforts for one negative size compared to another, and the available lens choices. If stimuli were to be eventually stored on videodisc, a film-to-tape transfer process would be required before the videodisc could be produced. The Rank-Cintel, a standard piece of equipment used in the industry for this purpose, can process either 16mm or 35mm negatives at 30 frames/s to NTSC-format videotape, but not 65mm negatives. Aside from higher initial filming costs with 65mm, a "printing down" to 35mm before transfer to tape would thus also have been required. Concerning lens choices, a much wider variety of high-quality lenses--providing combinations of field-of-view with depth-of-field that were particularly well-suited to present needs--were available for 35mm vs. 65mm filming. A more detailed discussion of factors affecting lens choice follows below.

In balancing the desire to maximize image resolution while minimizing "special effects" studio production costs, 35mm emerged as the best option for cinematic filming. Several options remained with respect to effective negative size within the realm of 35mm, however. These options concerned the filming aperture size, and thus the amount of the available negative area exposed on each frame. The standard Academy aperture (aspect ratio: 1.33/1) and the Cinemascope aperture (aspect ratio: 2.35/1) were the leading alternatives. It was determined in this task that the view through the windshield of a passenger car describes an aspect ratio between 2/1 and 3/1, depending on make and model.

Cinemascope involves the use of **anamorphic** lenses. This is a type of lens with special optical properties that can squeeze the horizontal dimension by a factor of 2 during filming, while leaving the vertical dimension unaffected. Since the camera sees twice as much in the horizontal plane through an anamorphic lens, the focal length in the horizontal is effectively halved, i.e., a 50mm anamorphic lens can be compared to a 25mm spherical lens. Most importantly, however, is the fact that the anamorphic system uses 100 percent of the available negative area, and "undoubtedly produces the finest image quality of any 35mm wide screen format."[21]

The Cinemascope 35mm format was thus identified as the most desirable, and feasible, option for cinematic filming of test stimulus scenes. It was further decided at this point that a film-to-tape transfer allowing images recorded in 35mm to be stored on videodisc would be recommended, while still preserving the option of directly projecting the (edited) 35mm filmtrack to subjects in the laboratory simulator.

LENS SELECTION FOR RECORDING TEST STIMULI

The choice of a specific lens for filming determined the field of view that would be obtained for each camera used, the quality of the recorded image in terms of clarity and distortion, and, most importantly, the verisimilitude of the perspective (visual angle relationships) displayed in a driving scene in the simulator to that seen by a driver under comparable real-world conditions. Since the experimental measures addressing time-to-collision and gap judgments were grounded in hypothesized age differences in the capability to perceive angular expansion information for distant vehicles, the preservation of correct perspective in laboratory test stimuli was deemed essential to the validity of this research.

Regarding the field of view requirements, the desire to obtain 180° or more in the overall simulator configuration, and the planned use of flat vs. curved projection screens, dictated a system design where three screens would be needed for the display of driving test scenes: (1) a forward (front windshield) view, (2) a driver's side window view, and (3) a passenger's side window view. The geometry of a conventional vehicle (sedan) interior in turn dictated the need for a field of view displayed on each screen--and therefore recorded by each camera during filming--of between 70° and 80°.

Wide angle lenses, noted for their ability to capture a large horizontal field of view, also are associated with problems of image distortion and loss of correct perspective, particularly at the edges of the image. At this point, the definition of a normal, or distortion-free lens, deserves a brief comment. The convention of defining the normal lens for any format of photography is purely arbitrary. That is to say that for still photography, the normal lens for any format is defined as the focal length in millimeters equal to the diagonal of the photographed image. A 35mm still frame produces an image 24 mm by 36 mm. This yields a diagonal of about 43 mm, which would be considered a normal lens. It should be noted that since this convention is arbitrary, any lens approaching 50 mm is generally accepted as normal. The definition of a normal lens for motion picture photography is similar in that it is defined as the focal length in millimeters equal to twice the diagonal of the photographed image. This yields a normal lens of 54 mm for Academy 35mm, and one of 115 mm for the 65mm format.

Correct perspective is a function of both the photographed image, and the position of the observer at the time of projection. A projected image is being viewed in proper perspective (or center of perspective) when all objects in the picture are in proportion to the original scene **as it appeared from the position of the camera lens.** Maintaining proper perspective is crucial when the scene contains large amounts of three-dimensional information. If a scene is viewed from behind the center of perspective, foreground images will appear disproportionately large, and depth is exaggerated. Objects moving either toward or away from the lens will appear to be moving at a greater than normal speed. When a scene is viewed from in front of the center of perspective, the exact opposite is true; axial motion appears slower, and images are compressed. While these parameters may appear difficult to balance, they can be related by a simple formula: **a projected image is being viewed in proper perspective if the viewer is located a distance away from the image equal to the magnification of the picture times the focal length of the lens used to photograph the image.**[22]

The above variables governing proper perspective were applied to the design of the planned driving simulator to yield specific guidelines for the system. As concluded earlier, the image recording recommendation was to film cinematically using a 35mm anamorphic format. To proceed with lens selection, assumptions about the exact image magnification required for simulator display as well as the position of the observer (test subject) in the simulator were needed. To ensure a level of visual accommodation in the laboratory that compared as favorably as possible to a driver's accommodation to vehicle targets under real-world conditions, an eye-to-screen distance of at least 8 ft (2.5 m) was recommended by the Scheie Eye Institute at the University of Pennsylvania. This simulator design attribute was deemed of critical importance in providing a sense of realism to test subjects in the laboratory. At this viewing distance, horizontal screen dimensions required to provide a field of view in the 70° to 80° range could be easily calculated. Then, the magnification factors relating (horizontal) image size on the screen vs. image size on the negative were derived; these calculations yielded an average value of 220.

Next, a formula provided in the *American Cinematographer Manual* was consulted that described the field of view afforded by a lens of a known aperture and focal length: field of view equals twice the arctan of the quantity one-half the camera aperture divided by the focal length of the lens.[22] Also taking into account that correct perspective is afforded by a viewing distance equal to the image magnification factor multiplied by the effective focal length of the lens, a 30mm anamorphic lens was identified as the best option for the filming of driving scene test stimuli.[22] This lens provided a distortion-free field of view of approximately 72°, at an effective focal length of .59 in (1.5 cm).

HARDWARE FOR IMAGE DISPLAY AND ENHANCEMENT

Hardware alternatives for displaying cinematic and video images to subjects in the laboratory were evaluated in this part of the simulator design feasibility study. Beginning with videodisc (laserdisc) players, evaluation criteria included sampling rates and speed of random access on a CAV disc, stand-alone features, expandability through external computer interfaces, reliability, and the availability of technical support.

The product emerging as the best buy in this evaluation was a laserdisc player with variable-speed drive capability. This capability made it uniquely suitable to simulate different driving speeds for the same test situation in the laboratory, thereby permitting a given dependent measure to be obtained under multiple test conditions without separate filming of each target vehicle approach (i.e., at different speeds). In addition to this technical superiority for its intended use in this project, this product was highly cost competitive. With an RS-232 serial port for external interface capability, the selected product was available at a price of approximately $2,000 in early 1991.

In conjunction with laserdisc player evaluation, existing technology for enhancement of NTSC signals was reviewed, given the concern that an NTSC image magnified for projection on a large screen would lose sufficient detail (high frequency spatial information) and compromise the validity of the laboratory measures. Formally labeled "improved definition television" (IDTV), this digital NTSC signal processing technique works in two different ways. First, it can interpolate to generate another horizontal line of information between each existing line on the display, where the information on every new line is created such that it fills in extra detail in the image consistent with the information just above and just below it. Alternatively, each existing line of information can simply be copied and scanned on the display adjacent to the originally recorded line. This latter approach effectively produces a signal that is non-interlaced, since line for line the same information is being scanned every second--one member of a pair of identical horizontal lines on the first pass, the other (copied) member of the pair on the succeeding pass. With the first approach, it remains an interlaced display where every other line is refreshed on any given pass. The same piece of hardware accomplishes both image enhancement strategies, going from one to the other with a single switch and working with a common (conventional NTSC) input signal.

Inspection of competing products in this task revealed that overall image resolution could be significantly enhanced with this technology, and the use of scan doubling for stimulus presentation in this research was therefore recommended. The digital scan converter identified as the best buy for this simulator application was available at a purchase price of $12,000 or a leasing cost of $4,000 per unit. Unfortunately, multiplexing of video inputs was not possible with devices of this type; i.e., a separate scan converter was needed for every player-projector in a display system.

Regarding the choice of video projectors for displaying the information stored on laserdisc to subjects in the simulator, the primary considerations were the brightness and resolution of the image. A preliminary search of technical/sales literature, followed by a visit to the National Association of Broadcasters (NAB) national convention by a project consultant, narrowed the options among competing product lines.

The comparison between competing products was directed specifically to the measured light output; the size of the internal raster (CRT) used to project the image in each device; the component signal (RGB) bandwidth, which dictates how high a frequency of signal--and consequently, how high the definition of the image--can be handled by each device; and the maximum screen size that can be accommodated with the standard lens on each device. Each product line offered a wide range of projector models, with varying areas of specialization. The brightest (highest light output) model may not offer the best contrast or resolution. To select a single, best-fit model for this research, a minimum screen size capability was first established, and the maximum brightness and resolution that could be achieved within that constraint was then sought.

The technically superior product based on these criteria achieved a rated brightness (peak) of 1,230 lumens, which was among the highest on the market; also, a 30-MHz bandwidth and 9-in (22.8-cm) internal raster (CRT) provided the best definition possible for the projected image using the NTSC signal format. Cost information obtained at the time this task was performed indicated a retail purchase price ranging from $18,500 to $20,000, and a rental price of $2,500/mo for the selected product.

SIMULATOR SYSTEM INTERFACES FOR DATA COLLECTION

To complete the feasibility study for the laboratory simulator design, the interfaces required for control of stimulus presentation and the recording of subjects' responses were defined. It was considered necessary for the video playback/projection system in the simulator to interface with a controller to ensure synchronized operation of multiple laserdisc players and to obtain disc address (frame) information to interpret a subject's response to the displayed driving scene stimuli. Specifically, a playback system incorporating three videodisc players and a personal computer (PC) with an 80386 microprocessor was envisioned at this stage of the system design. The recommended players contain sync ports, allowing for frame-by-frame synchronized playback of the units; further, the players are equipped with an RS-232 serial port that allows two-way communication with a PC. As noted above, this feature was one capability upon which the player selection was based.

These capabilities would permit a PC to control and monitor the function of the players through a command language understood by the players. This command language allows the PC to tell the players what part of the videodisc to play, when to begin and when to stop play, and at what speed to play the disc. The sync port ensures that once the commands are issued to the three units, they would begin and maintain synchronized operation. Further, when the PC commands the players to stop, it could also query the players as to which frame play was stopped.

The PC would require access to files on each scene to be played. These files would contain the target (stimulus) vehicle separation distance information for each frame of all the scenes. (A detailed explanation of how this information was collected and stored in these files is provided in later sections describing the methodology of the laboratory experiments.) The PC also would be required to monitor all instrumentation on the driving simulator (i.e., control pedals and steering wheel), so that when the subject makes a response it would be recorded in real time, and any related control of the players would be executed (e.g., stop presentation of scene).

The interface designed in this task would allow a PC to instruct the players to access the correct scene and begin playing, once the experimenter has selected a scene to be played back. The PC control via this interface would ensure that all three players start at the same time and remain synchronized. At the moment the subject makes a response, the PC could record the response, stop the video presentation, and query the players for the frame number at which playback stopped. Once the frame number is obtained, the computer could then look up the related separation distance in a file, as appropriate to either the time-to-collision or gap judgment trials. All of this information could then be displayed to the experimenter and recorded on disc.

For data collection involving cinematic instead of video projection in the laboratory, the interface requirements were the same except for the means by which individual frames on the film source were to be identified. It was determined that the PC controller would need a separate card enabling it to read SMPTE (Society of Motion Picture and Television Engineers) timecode. This timecode, placed on the filmtrack during the post-production process, would uniquely identify each frame. With frame identification by the PC, control over stimulus presentation and access of target stimulus distance information referenced by frame number could be achieved as necessary for the planned research.

PHYSICAL LAYOUT OF LABORATORY DRIVING SIMULATOR

Based on the technical information obtained in the feasibility study in this task, a simulator design reflecting the reported conclusions regarding screen size, field of view, viewing distance, and display hardware was prepared. As shown in figure 3, three views were provided in this design: forward (windshield), left (driver) side, and right (passenger) side. The boundaries between these views were designed to coincide with the left and right A-pillars in the simulator vehicle, which was fabricated using a compact car (4-door sedan) body.

A seamless through-the-windshield view of 72° (i.e., the field of view afforded by a 30mm anamorphic lens in 35mm filming) is shown in figure 3. This was to be obtained by slight padding of each A-pillar. The resulting design provided wider occlusion zones measuring 11° and 14° at the left and right boundaries of the forward field of view, respectively. This design feature was necessitated by the size and viewing distance constraints for the projection screens as discussed earlier, to ensure correct perspective of projected scene elements for a subject in the driver's seat in the simulator.

The proper-perspective design guidelines reported earlier are reflected in the simulator design shown in figure 3. The placement of the video projectors to the rear of each screen was based on technical advice from video engineers: the appropriate projector set-back distance was calculated by the formula $D = 1.31W + 18$, where W is the width of the screen and all units are measured in inches.

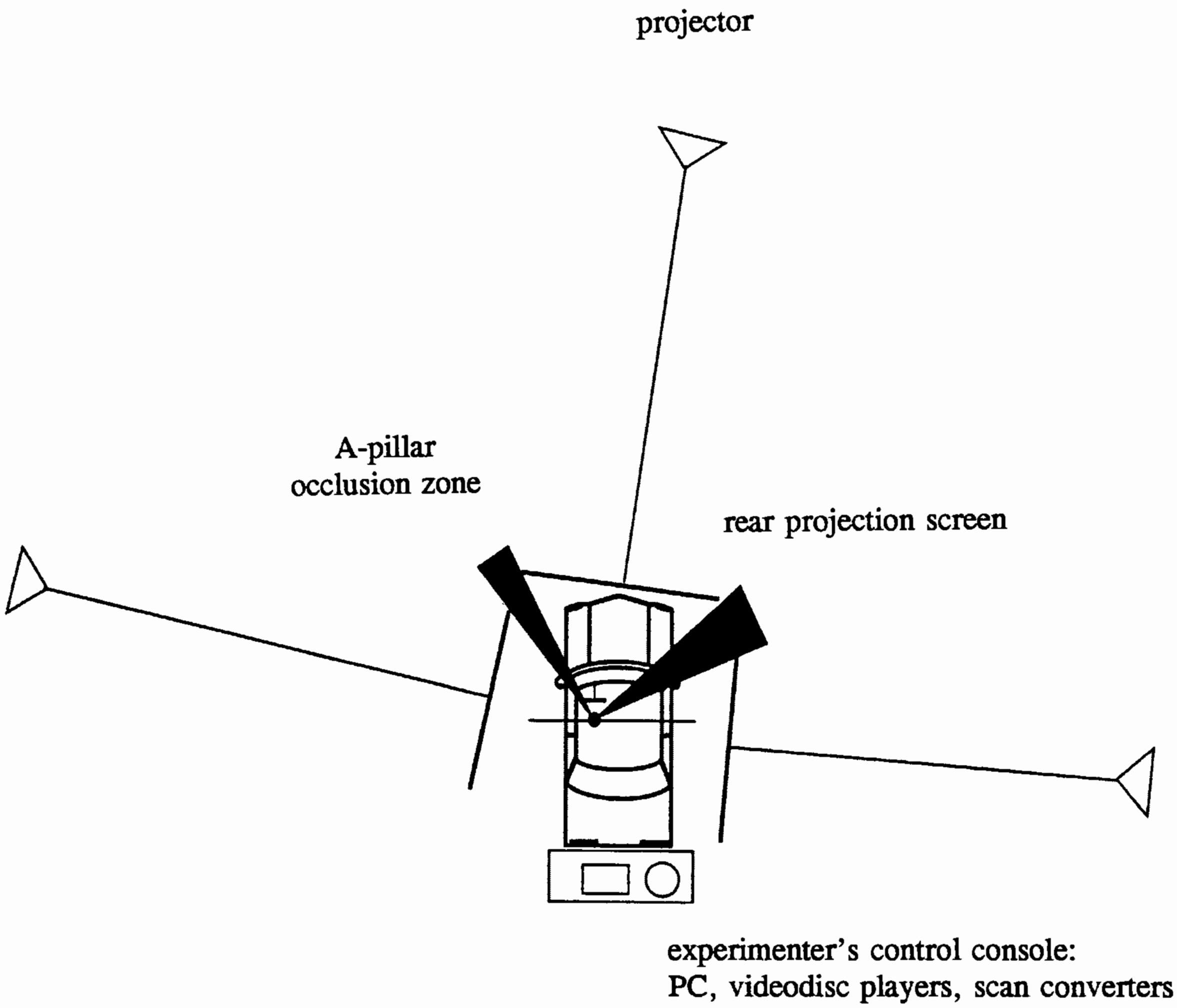


Figure 3. Plan view of laboratory driver simulator apparatus setup.

SAMPLE SELECTION

Procedures employed in the recruitment and comprehensive screening of prospective study participants, to characterize the test sample and to exclude individuals with pathological conditions and/or who represent extreme deviation from age-norms on key functional indexes, are reported in this section.

SAMPLE RECRUITMENT

The test sample for this research was drawn from three age groups associated in the technical literature with functional changes in human information processing capabilities underlying safe and effective driving performance. The "young/middle-age" driver group was comprised of drivers between the ages of 18 to 55. Age 55 was chosen as the cutoff for defining younger drivers, because at this age, decrements in visual capabilities are evidenced for some drivers, and individual differences within age cohort are beginning to show more exaggeration. Drivers over 55 years of age were divided into the "young-old" (ages 56-74) and the "old-old" (ages 75 and over) groups to preserve differences in cognitive, psychomotor, and visual capabilities exhibited by these two subgroups of older drivers.

In the interest of obtaining a representative distribution of driver capabilities, a quasi-random sample of test subjects was recruited through face-to-face, one-on-one solicitations at Pennsylvania photo license centers, where a person's birthdate (month of year) is the determining factor as to who appears on any given day. Additionally, individuals from a subject pool recruited in the same manner for a previous FHWA-sponsored study were invited to participate.[1] A sample size of 24 subjects in each age group was desired with some oversampling to counter possible attrition. Each prospective participant was advised that a total of $135 would be offered if he/she completed all phases of the study as follows:

- Laboratory sessions 1 and 2 (45 min each) = $ 35.
- Laboratory session 3 (2.5 h) = $ 50.
- Field study session (4 h) = $ 50.

The number of subjects (and their age statistics) initially recruited in each test group for this research is shown in table 2. As indicated, a majority of those recruited in each age cohort were male. Given the basic perceptual tasks at issue in this research, and a lack of evidence of reliable gender differences in relevant functional capabilities, the obtained male-female sample percentages were deemed acceptable. Actual sample sizes completing data collection requirements for each task are reported in the later tables of statistics describing test results.

Table 2. Characteristics of persons recruited for test sample.

Age Group	Number of Subjects	Number (%) of Males	Number (%) of Females	Age Range	Mean Age	Median Age
18-55	25	16 (64)	9 (36)	20-53	33.3	31
56-74	29	17 (59)	12 (41)	56-72	65.1	68
75+	25	16 (64)	9 (36)	75-91	79.4	78

SAMPLE SCREENING

Three visual performance measures and two cognitive screening indexes were obtained for each potential test subject. The vision screening tests were conducted using an Optec 1000 DMV (Stereo Optical Co., Inc.) vision tester to obtain measures of acuity, contrast sensitivity, and stereo depth perception, as described below. Cognitive screening indexes included the block design subtest of the revised Wechsler Adult Intelligence Scale (WAIS-R) and memory measures at two levels of difficulty (the forward and reverse digit span subtest of the WAIS-R). The rationale for employing these tests, and the testing and scoring procedures are described following the discussion of visual performance measures.

Acuity Testing. Binocular visual acuity was determined using a test slide containing five lines of Sloan letters (O, Z, H, N, R, K, S, D, V, C) combined into line lengths of from 12 to 15 letters, designed to measure acuities of 20/70, 20/50, 20/40, 20/30, and 20/20. Subjects were instructed to wear glasses if required for driving and to read aloud each of the letters on the first line (20/70), and proceed to each successive line. A subject was stopped when he/she missed two or more letters in a line. The acuity level of the line above the one in which two letters were missed was recorded as the subject's visual acuity score. The mean acuity levels found for the young/middle-age, young-old, and old-old subject groups were 20/24, 20/31, and 20/42, respectively.

Contrast Sensitivity. Contrast sensitivity was examined since it is logically related to a driver's ability to detect and track a target and then accurately judge its speed and distance, and because high and middle spatial frequency performance declines with age, especially over age 40.[23,24] Contrast sensitivity thresholds were obtained for sine-wave gratings with spatial frequencies of 6, 12, and 18 cycles per degree. An Optec test slide with the three contrast sensitivity tests was used for these measures.

Each spatial frequency test contains nine test patches, or circles, 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 grey 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 best threshold is obtained when a test subject can identify bars of the lowest contrast for each spatial frequency.

The subject was asked to look at each patch and to verbalize in which direction the bars were tilted. The threshold of the gratings in the highest numbered correctly read patch (prior to missing two consecutive patches) was recorded at each spatial frequency tested. Scoring of each subject's responses was either within a normal or was below normal range, according to published criteria pertaining to the overall population (i.e., norms were not adjusted for age).[25] The results obtained are shown in table 3.

Table 3. Percentage of age group in below normal range for measured contrast sensitivity spatial frequencies.

Age Group	Spatial Frequency CS-6	CS-12	CS-18
Young/Middle-Age (18-55)	32	4	0
Young-Old (56-74)	41	0	7
Old-Old (75+)	76	12	24

It should be noted that the 6-cycle targets were always presented first, followed by the 12-cycle targets, then the 18-cycle targets in the contrast sensitivity testing administered to subjects in this study. This protocol may have introduced a practice effect, which could help to explain the markedly depressed performance levels for all age groups for the 6-cycle targets.

The mean threshold contrast values for each age group at each measured spatial frequency are shown in table 4 and are graphed for ease of comparison in figure 4. Significantly, two subjects in the 56-74 age group and six subjects in the 75+ age group could not discern the orientation of the bars in the first test patch for the 18-cycle/degree test, and were thus excluded from the calculations of mean threshold values. The threshold contrast values listed below are therefore lower in these cases than if all test subjects were included.

Table 4. Mean threshold contrast for each age group as a function of spatial frequency.

Age Group	Spatial Frequency CS-6	CS-12	CS-18
Young/Middle-Age (18-55)	.013	.029	.051
Young-Old (56-74)	.020	.026	.054
Old-Old (75+)	.025	.056	.078

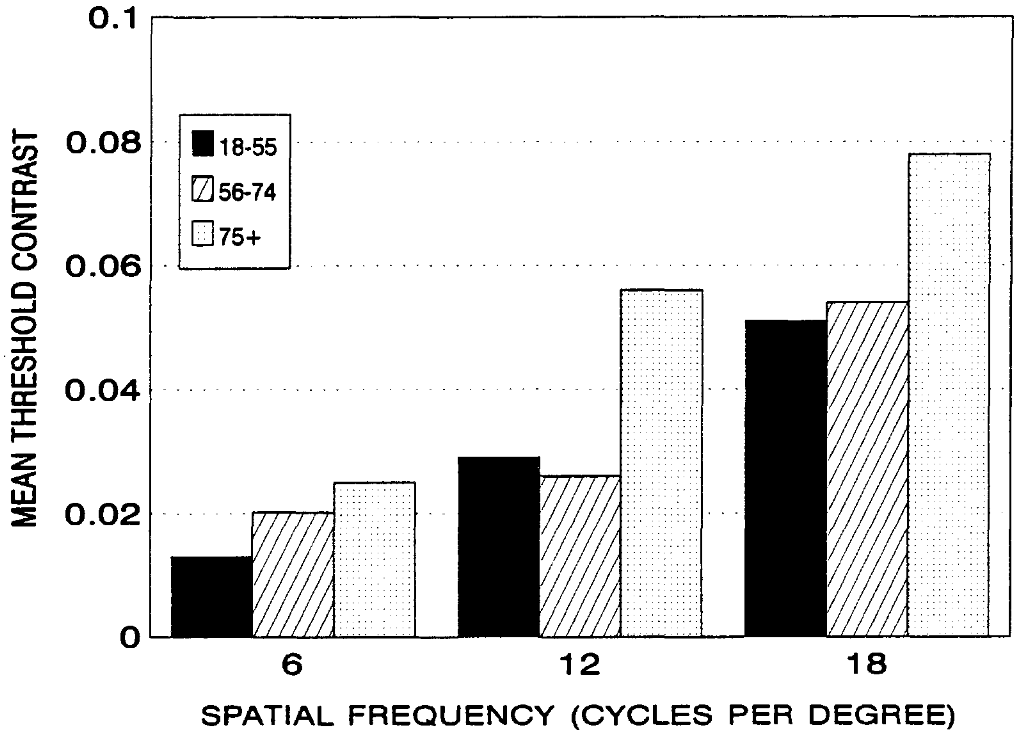


Figure 4. Mean threshold contrast as a function of age group and spatial frequency.

As expected, based on findings in the technical literature, the oldest age group showed the largest performance decrement at each spatial frequency tested.[26] Subjects in the young/middle-age and the young-old groups showed similar performance at the 12- and 18-cycles/degree spatial frequencies.

Stereo Depth Perception. This test was designed to examine a person's ability to judge relative distances without the aid of monocular cues. Logically, a person suffering a substantial decrement in this ability may evidence difficulty in gap acceptance judgments. The test slide consisted of six yellow diamond-shaped patches, each containing four black circles. One of the circles on each patch was designed to appear to be floating toward the subject. The angles of stereopsis (seconds of arc) tested were 400, 200, 100, 70, 50, and 40. The smaller the number, the more effectively an individual can discriminate the depth cues present in these stimuli.[27] Reading the first five circles correctly was scored as acceptable depth perception. If a subject missed two consecutive circles, the angle of stereopsis of the last correctly read circle was recorded as his/her depth perception score.

The mean results for the 18-55, 56-74, and 75+ age groups on this measure were 112, 117, and 217 seconds of arc, respectively, with standard deviations of 106, 103, and 140.

WAIS-R Block Design Test. This subtest of the Wechsler Adult Intelligence Scale (Revised) requires the ability to reason, analyze spatial relationships, and integrate visual and motor functions. The input information (pictures of designs) is visual, whereas the response (output) is motor; this generalized information processing sequence is broadly applicable to vehicle maneuver decisions. This test includes nine blocks, each measuring 1 in^3 (2.54 cm^3), and a picture book. Each side of each block is one of three colors: solid red, solid white, or half red and half white, divided diagonally. The subject's task was to arrange the blocks according to each of nine patterns depicted in the picture book.

The first five patterns used only four of the blocks, and the last four patterns utilized all nine blocks. The scoring sheet accompanying this subtest of the WAIS-R provides for a maximum of 60 s to complete designs 1 through 5, and 120 s to complete designs 6 through 9. Time to complete each design was entered on the score sheet. The number of points scored for each design was dependent on the time taken to complete the design as follows: for designs 1 and 2, 2 points were scored if the design was completed correctly on the first try within 60 s, and 1 point if completed correctly on the second try within 60 s. Subjects were given only one chance to correctly complete designs 3 through 9; for each design, 4 points were awarded for completion within the time limit, and from 1 to 3 bonus points were given for quick perfect performance, for a maximum score of 51 points.[28]

As described in the WAIS-R manual, the raw scores were converted to scaled scores based on a reference group that consisted of 500 subjects in the WAIS-R standardization sample between the ages of 20 and 34.[28] This age range was selected in light of evidence that performance on most tests reaches a peak somewhere within this age span. Accordingly, each subject's test results for this project were first compared with that of the WAIS-R reference group. Next, it was also possible to compare an individual's performance with that of persons in the same age group using age-scaled scores provided by Wechsler. The WAIS-R standardization sample consists of 9 age groups, each containing from 160 to 300 cases. This comparison is somewhat different than comparing an individual's scores with those of the reference group. For example, an individual who is 60 years old and receives a raw score of 29 on the Block Design test would receive a scaled score of 9 when compared against the reference group, and an age-scaled score of 12. This same raw score would put this individual in the 37th percentile (below average) of the reference group, and in the 75th percentile (above average) of his/her age-peers.

When compared with the reference group, 96 percent, 69 percent, and 32 percent of the young/middle-age, young-old, and old-old test subjects, respectively, performed at least as well as or better than 95 percent of the reference group. Twelve percent of the old-old test subjects performed below average (received scores that placed them below the 50th percentile), whereas only 3 percent of the young-old, and none of the young/middle-age subjects scored below average. When the performance of each group was compared with the performance of their age-peers, however, 100 percent, 97 percent, and 88 percent of the young/middle-age, young-old, and old-old subjects, respectively, performed as well as or better than 95 percent of the age-peer group. Only one test subject in the old-old age group performed worse than 50 percent of his/her age-peers, receiving an age-scaled score at the 25th percentile level. Comparisons showing the performance of each age group, referenced to both the 20-34 years of age WAIS-R standardization group and scaled in terms of age-peer equivalent scores, are graphed in figures 5, 6, and 7, for the young/middle-age, young-old, and old-old test samples, respectively.

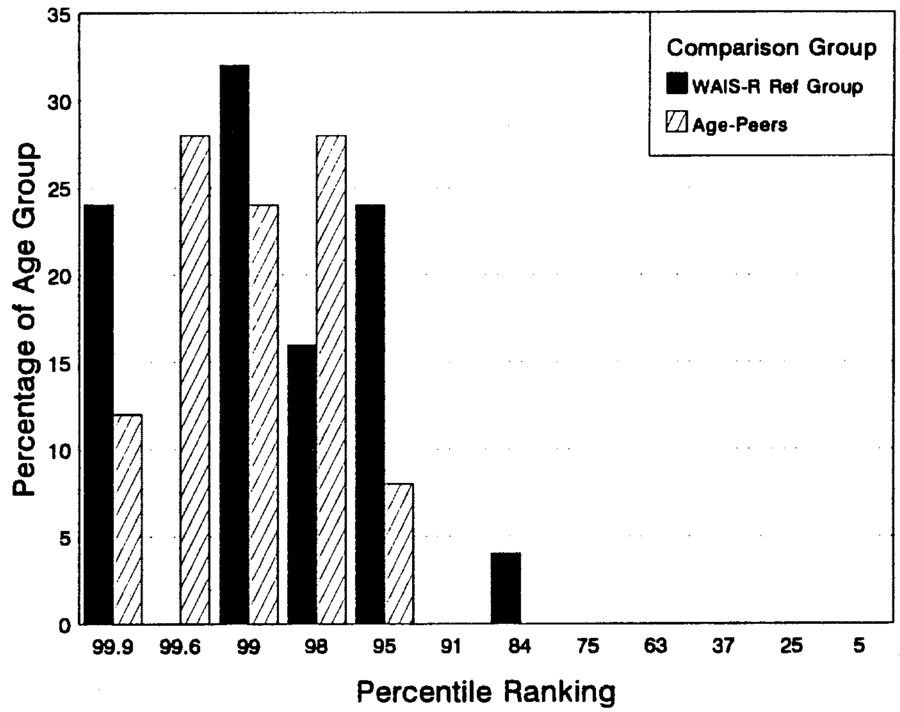


Figure 5. Young/middle-age group performance on the Block Design test, in relation to cited comparison groups.

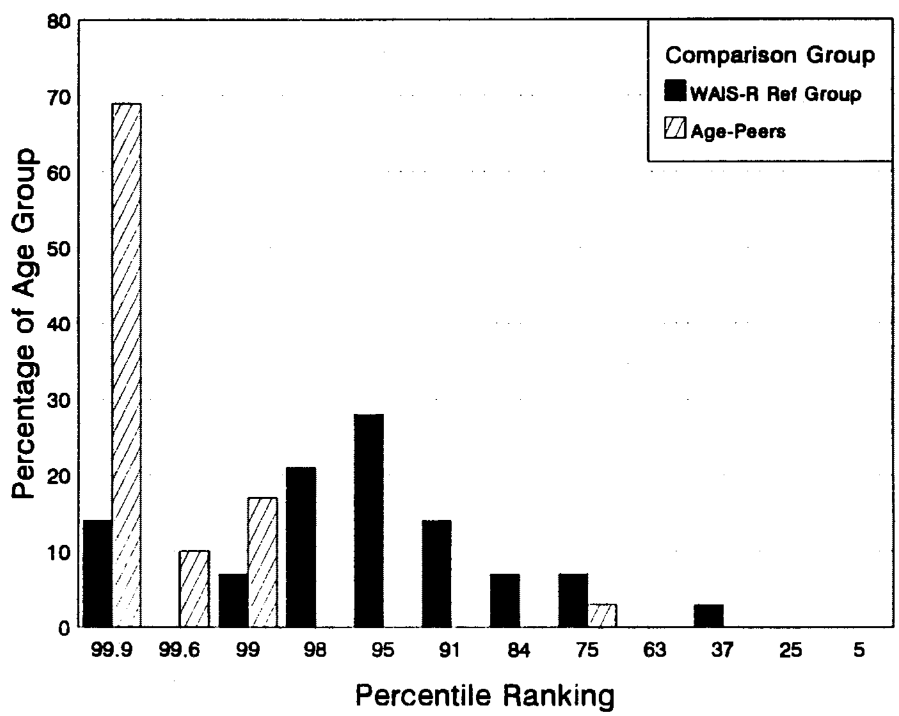


Figure 6. Young-old group performance on the Block Design test, in relation to cited comparison groups.

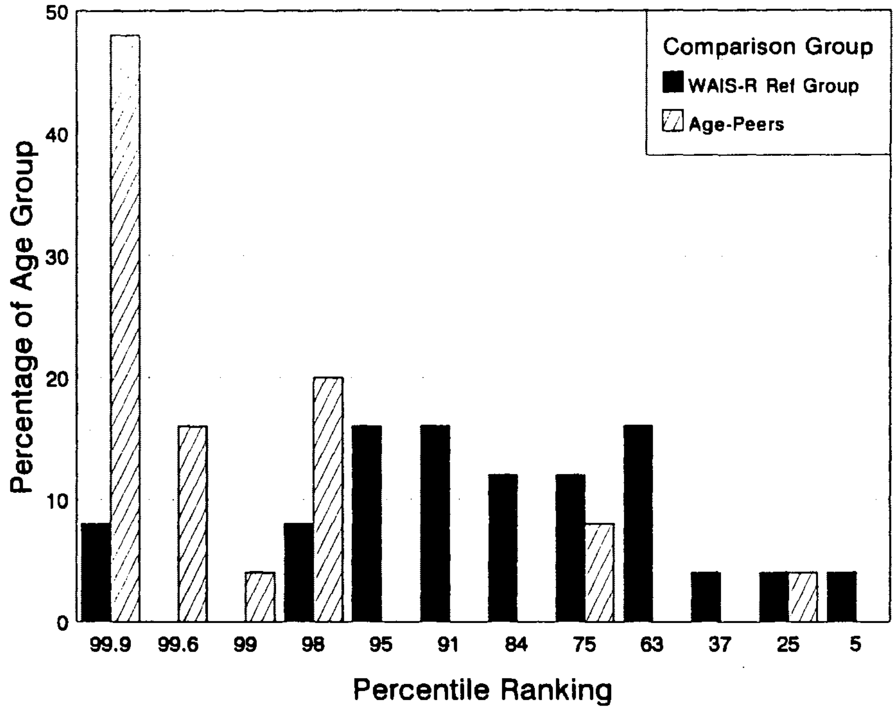


Figure 7. Old-old group performance on the Block Design test, in relation to cited comparison groups.

Digit Span Tests. The use of the forward and backward digit span test provided a reliable means of describing differences in test subjects' abilities to store and manipulate discrete items of information in short-term, or immediate memory. Also important to the operations of working memory, this human information processing function permits the integration of sensory input over time to hold current information available briefly for more complex cognitive operations, such as decision-making and problem-solving. This functional capacity is essential for virtually every aspect of the driving task. Studies of working memory show an age effect in performance favoring younger over older persons, thus older drivers will be most at risk in situations that require rapid mental operations for vehicle control, especially when they are required to perform such operations and retain other information for future use.[29,30,31]

The forward digit span consisted of (audio) taped sequences of digits ranging in length from 4 up to as many as 11 in length, presented monaurally over headphones. Subjects were immediately required to repeat the sequence back to the experimenter, in the same order as heard on the tape. Two different sequences of digits at each length were presented to give a subject a second chance to correctly repeat a span length before proceeding with a span of more digits. The task was terminated when a subject missed two attempts at a given sequence length, with immediate memory span defined as the longest sequence where at least one attempt (out of two) was correct.

The reverse digit span contained taped sequences of digits ranging in length from 3 to 10 digits. The subject's task was to repeat the digits in the reverse order from that heard on the tape. Scoring for the reverse span was the same as that for the forward span.

The mean number of digits repeated correctly by each age group for the forward digit span was 6.96, 6.69, and 6.20 for the young/middle-age, young-old, and old-old groups, respectively. For the reverse digit span, the mean number of digits repeated correctly was 5.68, 5.14, and 4.68, for the age groups as reported above. As expected, a modest decline was shown as a function of age for both the forward and the reverse digit span tests.

Digit span forward and reverse scores were combined as described in the WAIS-R manual to yield a single raw score for this subtest. The raw scores were converted to scaled scores for comparison with the WAIS-R reference group, as previously recounted for the Block Design test. When compared with the reference group, 76 percent, 69 percent, and 48 percent of the young/middle-age, young-old, and old-old groups, respectively, measured as well as or better than 50 percent of the reference group on this performance index.

Age-scaled scores were also obtained to contrast the performance of each test group with that of individuals in their respective age groups. As expected, an increase in the number of test subjects in all age groups performing above average was observed when their performance was compared with that of individuals in their own age cohorts. Of the young/middle-age, young-old, and old-old subjects, 84 percent, 76 percent, and 72 percent respectively, performed as well as or better than 50 percent of the WAIS-R subjects tested in the same age groups. Figures 8, 9, and 10, describe performance in relation to the WAIS-R standardization group and to age-peers for the young/middle-age, young-old, and old-old groups, respectively, on the digit span screening measure.

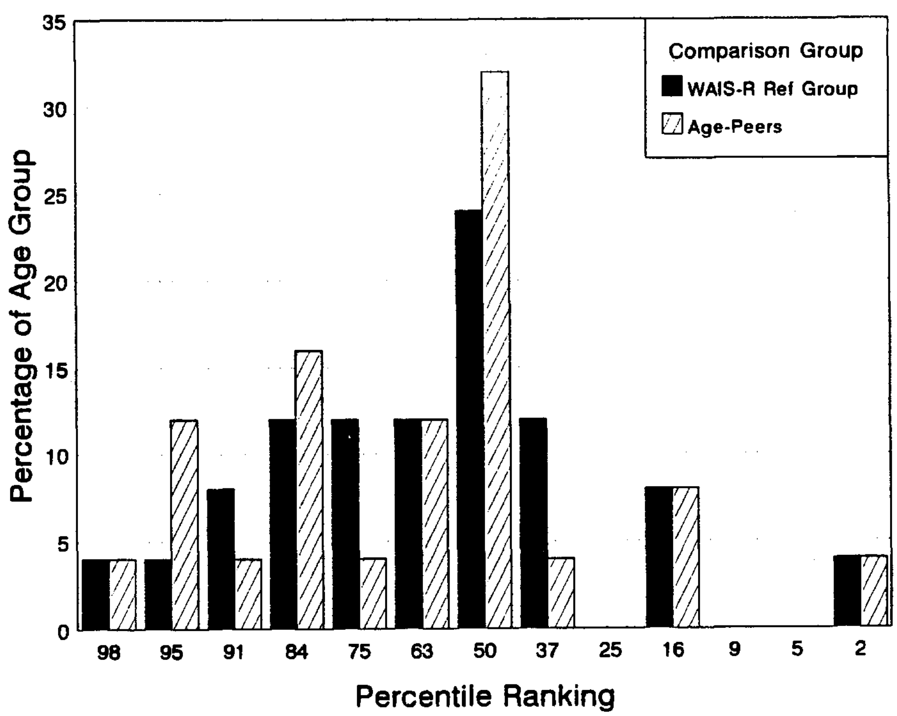


Figure 8. Young/middle-age group performance on the WAIS-R Digit Span test, in relation to cited comparison groups.

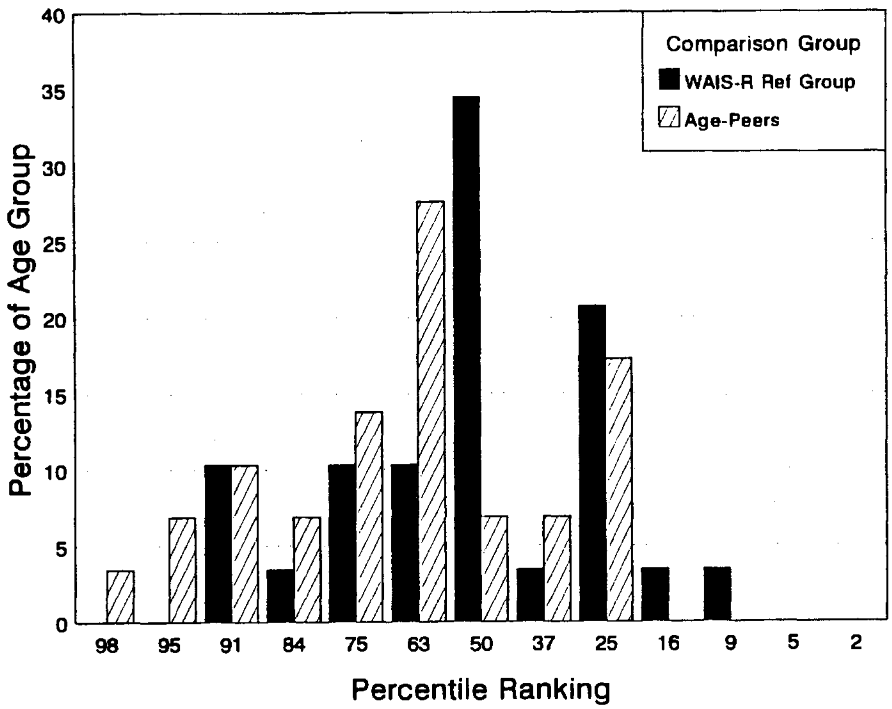


Figure 9. Young-old group performance on the WAIS-R Digit Span test, in relation to cited comparison groups.

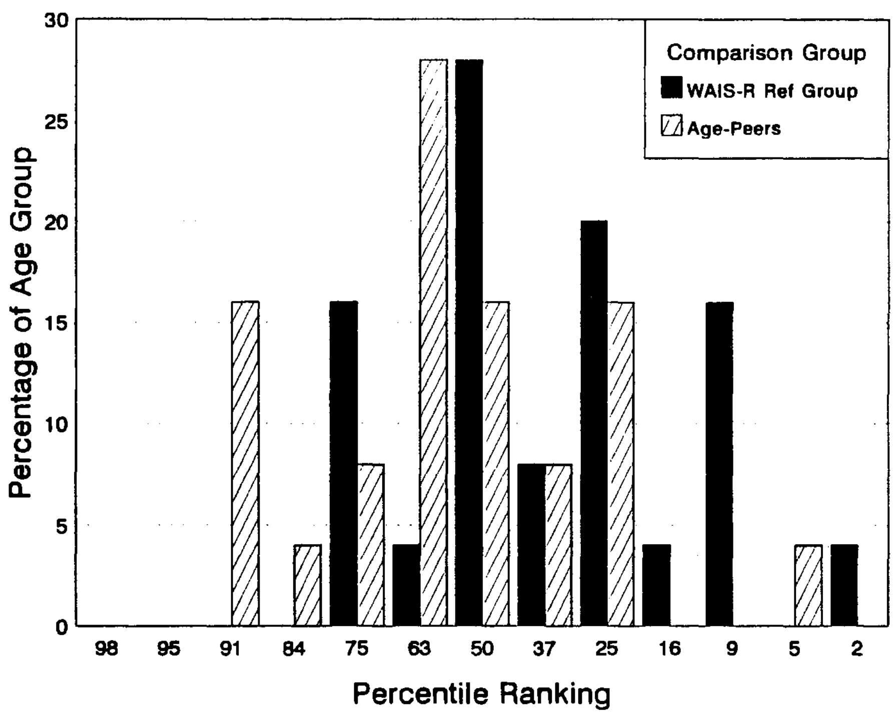


Figure 10. Old-old group performance on the WAIS-R Digit Span test, in relation to cited comparison groups.

MOTION JUDGMENT EXPERIMENTS

The age differences in motion perception reviewed earlier served as the starting point for laboratory and field testing of older and younger drivers' motion judgment capabilities as required to safely complete specific traffic maneuvers. The experimental procedures for the laboratory (simulator) studies and the field study are described initially in this section, including subsections for each effort that explain the objectives, experimental variables, test conditions, test apparatus, test stimuli (test sites/stimulus preparation), and the data collection protocol. A combined results and discussion section follows.

LABORATORY DATA COLLECTION USING DRIVING SIMULATOR

Objectives. The objective of the motion judgment study was to measure age-related differences in drivers' capabilities to accurately judge the time-to-collision (TTC)--from a driver's-eye perspective--of (simulated) approaching vehicles, in non-traffic situations, from both stationary and moving positions. An additional objective of the laboratory studies was to determine the suitability of different wide-field-of-view ($\geq$ 180°) simulator display methodologies for collecting the driver performance measures of interest. Data collection methodologies used in the laboratory to display stimulus scenes included: (1) a large-screen videodisc-based simulator, (2) a large-screen cinematic-based simulation system, and (3) a television monitor-based system.

Experimental Variables. The motion judgment laboratory study included four independent variables and one blocking variable. The independent variables were:

- Angle of conflict vehicle approach: 2 levels = head-on, 90°.
- Conflict vehicle approach speed: 3 levels = 30, 45, and 60 mi/h (48, 72, and 96 km/h).
- Actual TTC: 3 levels = 2.5 s, 5.0 s, and 7.5 s.
- Age (group) of drivers/subjects: 3 levels = 18-55, 56-74, and 75+ years of age.

The blocking variable was the frame of reference of the observer, either stationary or moving. The dependent variables in the motion judgment laboratory study were the recognition distance for an approaching (conflict) vehicle on each trial, and the estimated time-to-collision (TTC) with that conflict vehicle.

Experimental Design. The independent variables were not completely crossed, i.e., the levels and combinations of levels changed for some variables across the stationary vs. moving observer blocks of test trials. To begin, both angles of approach of the conflict vehicle were examined for the stationary observer trials. For the moving observer trials, however, only a head-on approach angle for the conflict vehicle was shown. Next, the speed of the conflict vehicle was examined at all three levels for the stationary observer block of trials, using the videodisc methodology. For the moving observer block of trials, the same three conflict vehicle speeds were examined, with each speed matched to the observer's vehicle speed. That is, when the observer's vehicle was moving at 30 mi/h (48 km/h), the conflict vehicle speed was also 30 mi/h (48 km/h); when the observer's vehicle was moving at 45 mi/h (72 km/h), the conflict vehicle speed was 45 mi/h (72 km/h); and when the observer vehicle speed was 60 mi/h (96 km/h), the conflict vehicle speed was 60 mi/h (96 km/h).

For data collection using the cinematic and television monitor display systems, however, conflict vehicle speed was manipulated only at 30 mi/h (48 km/h) and 60 mi/h (96 km/h). In all other respects, the above discussion of independent variables for videodisc data collection in the motion judgment study also pertained to data collection using cinematic and television monitor methodologies. The three levels of the actual TTC variable were constant across both the stationary observer and the moving observer blocks of test trials. Also, the three driver age groups, with the same subjects participating in all test conditions (using a repeated-measures design), defined the levels of the driver age variable in both the stationary observer and the moving observer blocks of trials, for all stimulus presentation methods.

Test conditions. The test conditions defined by the combinations of the independent and blocking variables as described above are diagrammed below for the videodisc, cinematic, and television monitor methodologies. A test conditions matrix for the motion judgment study using the videodisc methodology is shown in figures 11 and 12 for the stationary observer and the moving observer blocks of test trials, respectively. Figures 13 and 14 show stationary and moving observer test conditions, respectively, for data collection using cinematic and television monitor display systems.

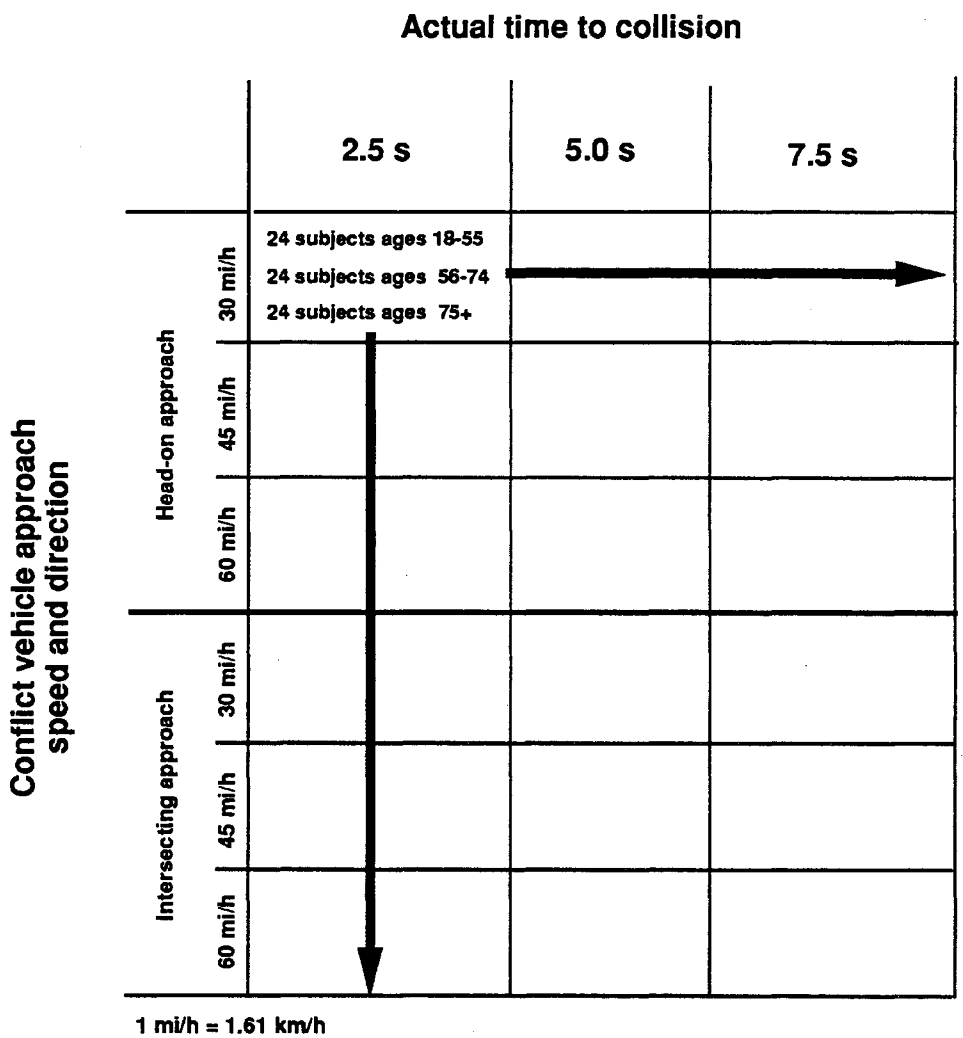


Figure 11. Motion judgment laboratory study test conditions: stationary observer and large-screen video methodology.

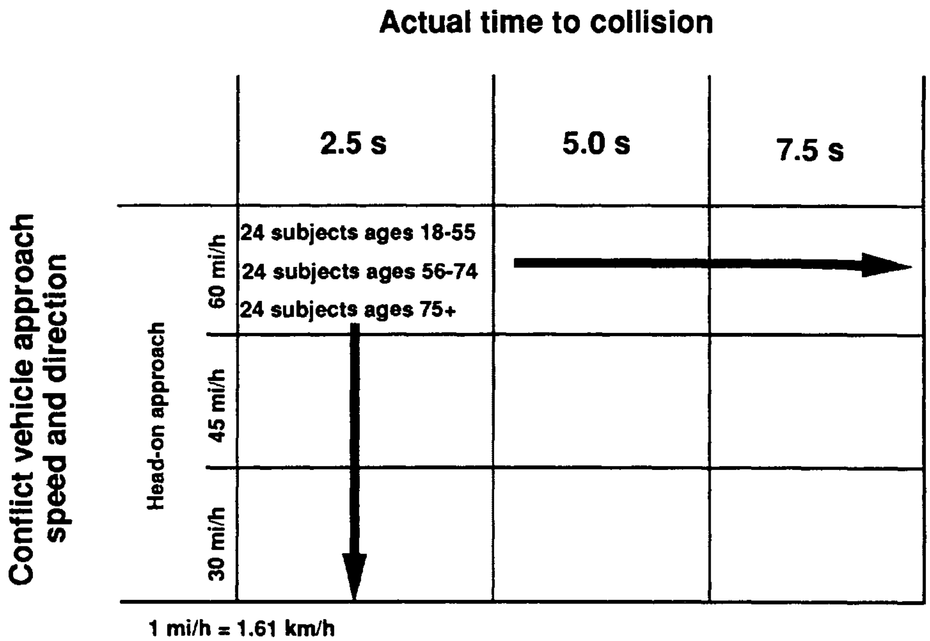


Figure 12. Motion judgment laboratory study test conditions: moving observer and large-screen video methodology. [Note: observer vehicle speed matched speed of conflict vehicle (30, 45, and 60 mi/h (48, 72, and 96 km/h)) for any given test trial.]

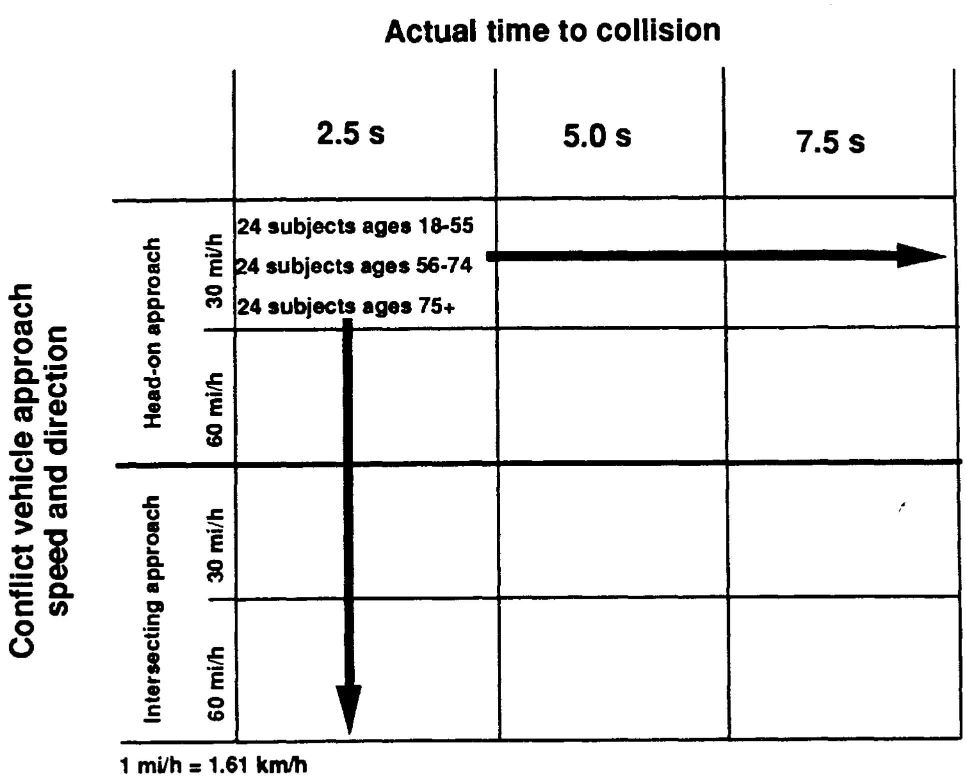


Figure 13. Motion judgment laboratory study test conditions: stationary observer, cinematic, and television monitor methodologies. [Note: static images were shown in fields of view where subject's attention was not directed.]

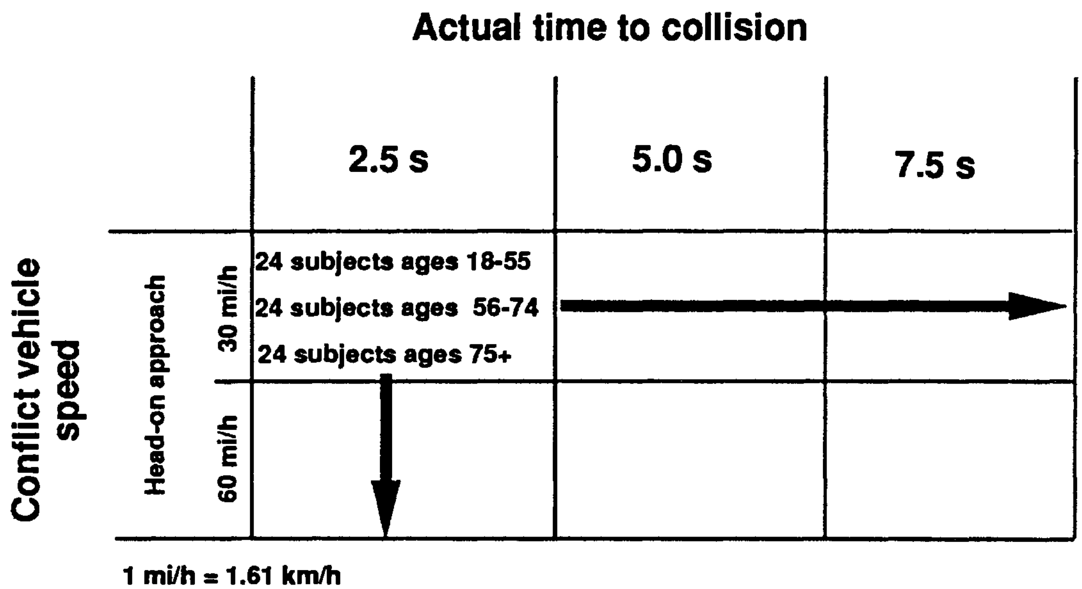


Figure 14. Motion judgment laboratory study test conditions: moving observer, cinematic, and television monitor methodologies. [Note: observer vehicle speed matched speed of conflict vehicle for any given test trial, and forward (windshield) view only was presented (i.e., no left side or right view sides were shown for moving observer trials).]

Test Apparatus. The apparatus used for laboratory data collection for the motion judgment study was the large-screen driving simulator described earlier in this report, plus a television monitor system arranged around a subject seated in a chair instead of in a vehicle. The same videodisc source was used for the large-screen video and television monitor methodologies.

The layout of the simulator for both cinematic and large-screen video data collection was consistent with the drawing in figure 3, with one important distinction: three video projectors were used to display roadway scenes during large-screen video data collection, while cinematic data collection used a 35mm film projector for one of the three screens--wherever the target (conflict) vehicle appeared--and 35mm slide projectors were used to display static background images on the remaining two screens, on stationary observer test trials. Specific items of hardware used in the simulator are listed as follows:

- Video projectors: Barcodata 1001.
- Videodisc players: Pioneer LD-V8000.
- Scan converters (NTSC): Ikegami DSC-1050S.
- Rear-projection screens: Stewart Lumiflex 180.
- Television monitors: Sony, Panasonic 20-in (51-cm) color televisions.
- 35mm cinematic projector: 30 frames/s, with anamorphic lens.
- 35mm slide projectors: Kodak Ektagraphic.

In the set up of the large-screen simulator for videodisc and cinematic data collection, dimensions indicated in figure 3 as required for correct-perspective viewing of the projected images were carefully adhered to. A screen horizontal dimension of 108 in (274 cm) and a driver-screen separation distance (on-axis, normal to screen surface) of 74 in (188 cm) was provided in the simulator. The set-back of each video projector behind its screen was approximately 159 in (404 cm). Set-back for the cinematic projector was adjusted to achieve an in-focus image of the exact horizontal dimensions [108 in (274 cm)] desired to maintain correct-perspective roadway views.

The vehicle enclosure used for the large-screen simulator incorporated a Fiat 4-door sedan with the gas tank, engine, and rear windshield glass removed. Adjustable bucket seats were retained in the front, on both driver and passenger sides of the car; the rear seats were removed and a flat bench was installed to serve as an equipment platform. The engine and gas tank were removed for safety and to make the vehicle body easier to move into position in the laboratory.

Steering wheel motion and accelerator and brake pedal depression in the large-screen simulator were monitored by switches that were sampled by a PC with an 80386 microprocessor, coded with Microsoft QuickBASIC software. This level of computer and software yielded a sampling rate of one observation/1 to 2 ms.

In addition, the steering wheel in the large-screen simulator was instrumented with a response button, with which the subject indicated his/her recognition of the approaching vehicle test stimulus on each trial. This button was a discrete "on-off" switch; the instant at which a subject pushed this button was translated to a specific frame of the videodisc or 35mm cinematic display, which in turn was associated with the separation distance from the observer based upon the computer log recorded at the time of filming.

For moving observer trials, a concurrent tracking task was employed to simulate the cognitive, perceptual-motor integration demands upon drivers when they execute steering control movements to center a visual referent, such as a point on the hood or front corners of a car, between two limits of lateral displacement, as defined by the lane edge on a roadway. While this activity requires a small fraction of a driver's overall processing capability under all but the most adverse of conditions, it nevertheless represents a measure of cognitive effort that must be taken into account as a subsidiary task whenever higher cognitive functions, such as judging distance and speed of an oncoming vehicle, are studied. The task required subjects to keep the tracking target--a dot on an IBM PC/XT screen--from laterally straying off the CRT display. Turning the steering wheel controlled the movement of the target, the motion of which was consistent with that of a massive object possessing inertia, yet slowed by a substantial frictional component. The instability of the task, or task difficulty, was set at a low level, requiring subjects to devote the minimal attention typically required to keep one's car from straying off the edge of the road during normal driving conditions. The tracking task display was located on the hood of the simulator vehicle, integrated into the vehicle dashboard.

For the television monitor setup used for laboratory data collection, three 20-in (51-cm) television monitors were situated at right angles to one another--in front, to the left, and to the right of the test subject. With the subject seated, the television displays were in line with the subject's eye height. The gaps between the edges of the monitors (as the subject faced them) were filled in with flat, matte black panels that extended from the edges of the center (front) monitor to the near edges of the left and right side monitors. The tracking task display was recessed just below the center (front) monitor; its position relative to the front monitor was analogous to the location of the tracking task display using the large-screen systems (i.e., in the hood of the simulator vehicle). The viewing distance of the test subject from each of the three television screens was 24 to 26 in (61 to 66 cm).

To obtain the desired measures of effectiveness in the laboratory using the television monitor methodology required a different (but related) set of response mechanisms than those implemented in the large-screen simulator. A steering wheel again controlled the subsidiary tracking task, and a response button mounted on the wheel was again employed to allow the subject to signal the initial point at which he/she recognized that the approaching object was an automobile in each test scene. The steering wheel was attached to a framework that supported the various monitors needed in this approach, instead of being integrated into a vehicle dashboard as it was in the large-screen simulator. Similarly, a brake pedal installed in the supporting framework allowed subjects to perform estimated time-to-collision judgments. Thus, while the specific apparatus used for the television monitor methodology differed from the large-screen simulator, the location and actuation of response mechanisms paralleled those employed in both the large-screen video and the 35mm cinematic stimulus presentation efforts.

Data collection using the large-screen video methodology in the simulator was accomplished in an initial laboratory session, on a one-subject-at-a-time basis. Data collection using the cinematic and television monitor methodologies was accomplished in a following session, for each study participant.

Test Stimuli. The vehicle that served as the filming platform was a Plymouth Duster modified to accept three Panavision cameras in an orientation appropriate to capture forward, left side, and right side fields of view as desired for playback in the simulator. A rigid mount was fabricated and attached to the car body that provided for exact vertical alignment of the multiple cameras; this was crucial if the horizon lines and top and bottom frame lines were to be perceived as continuous when viewing the scenes recorded by the various cameras. The vertical placement of the cameras provided for a simulated driver eye height approximating 42 in (107 cm), and the cameras were aimed horizontally to achieve the fields of view depicted earlier in figure 3.

The vehicle serving as the target stimulus (conflict vehicle) for the motion judgement test trials was a white, full-sized American sedan (Mercury Marquis).

Next, a critical element for the success of the visual presentation in the driving simulator was the synchronization of the three cameras used to film the various traffic scenes. Only proper synchronization at the time of filming would permit synchronized playback during the laboratory study. To ensure this camera synchronization, a customized system was designed, which linked and synchronized the three cameras by using two phase synchronizers. One of the three cameras was designated as the lead camera (camera #1). As this camera began to film, it generated a pulse train with a frequency of one pulse per frame. This pulse train was monitored by synchronizer #1, which in turn drove camera #2. This strategy was repeated for synchronizer #2 and camera #3. Additionally, another line was connected to camera #3 so that the pulse train could be monitored by a monitoring computer in the filming vehicle. The entire system attained correct filming speed and perfect synchronization in less than 2 s after filming was initiated at camera #1.

After the three cameras had come up to speed, it was necessary to stamp the film in each camera with a physical mark that could be viewed during editing. This stamp was provided by three LED's (one for each camera) that were wired together and connected to a common switch. The first frame that showed an illuminated LED was designated frame #1. At the time of this stamping, the switch closure that lit the LED's also sent a pulse to the monitoring computer in the filming vehicle so that the data file that counted the frame pulses from the cameras could be referenced to the stamp on the film. The computer only recorded pulses after the stamp pulse was received, thus ensuring that frame #1 in the computer record corresponded to frame #1 on the actual film.

At the time the various driving scenes used as test stimuli in the laboratory study were filmed, all related information needed for interpretation of subjects' responses in the simulator were also recorded, such as the instantaneous separation distance of the filming vehicle and the target vehicle used in any given scene. Since a subject's motion judgment response could occur at any time for a given scene, the separation distance information was required for each frame recorded. This was accomplished as described below.

The driving scenarios consisted of two principle elements: the filming vehicle and a target (conflict) vehicle. The filming of each scene required that the distance separating these two vehicles be recorded each time a frame of film was exposed. Since the scenes were filmed at 30 frames/s, 30 distance measurements were made and recorded every second. As noted above, the filming vehicle provided the platform for three fixed cameras with their shutters synced together (exposing film at a rate of 30 frames/s). The filming vehicle also contained a Transwave/Nu-Metrics RoadStar Series distance measuring unit (DMU) that was wired into the transmission, and a portable computer to record all data. Similarly, the target vehicle contained a DMU and a portable computer.

Both position and time were accounted for to accurately determine the separation distance between the filming and target vehicles for each frame of film. Both of these parameters were provided by the DMU's, in conjunction with accurate real-time clocks attached to the monitoring computers. The computer in the filming vehicle monitored pulses sent from each camera and its DMU. A camera pulse was sent each time a frame was exposed, and a DMU pulse was sent for each foot (.3048 m) traveled. The computer monitored and counted these pulses and recorded the camera pulse count, the distance count, and the exact time (to 1/100th of a second) each time a frame was exposed. There was no camera on the target vehicle, so the computer needed only to record the distance count and the time for each distance pulse.

Each vehicle started from an exact, known location marked in advance, and traveled on a predetermined path. This way the exact position of either vehicle could be determined by referring to the distance traveled at any time. The separation distance data was calculated and stored in a look-up file used during data collection, as noted earlier. The separation distance was computed by noting the distance and time associated with each film frame. The distance recorded with the frame number in question gave the position of the film vehicle relative to its original position. By referencing that same time, the computer record of the target (conflict) vehicle revealed the distance/position of the target vehicle at that exact moment; the direct calculation of each vehicle's distance from its known starting point thereby yielded the separation distance of the two vehicles. This system offered a high degree of flexibility in that the vehicles were not required to be in communication with one another. Because they started from a known location, and moved along a predetermined course, their relative and absolute positions were simple to calculate.

The procedures described above provided all time and distance information needed to interpret a subject's response to stimuli stored and played back on videodisc. Test stimulus preparation for cinematic-based data collection required additional work, however, as described below.

The preparation of 35mm cinematic stimuli for data collection involved the production in the laboratory of two film prints--one showing conflict vehicle approach speeds as filmed and another showing conflict vehicle approaches at an apparent increase in speed for conditions of interest as identified in figures 13 and 14. The speed of the conflict vehicle as filmed was 30 mi/h (48 km/h), and the increased speed for selected conditions was 60 mi/h (96 km/h). Thus, the first answer print incorporated views of the target vehicle as recorded on the original negatives from the front and left side cameras; the second print was optically "skip printed" (every other frame printed) to show the same material at twice the normal rate of speed. Slides were produced to display the static stimulus scene as viewed through the windows where the approach of the conflict vehicle did **not** take place, i.e., the right side view and either the front or left side view, depending upon trial type.

Each answer print as described above also contained a SMPTE (Society of Motion Picture and Television Engineers) timecode laid down on the optical sound tracks. This timecode provided a means of identifying any given frame number as it was projected, allowing the localization of a subject's response to a specific frame after the fact. That is, the PC used to record data in the laboratory monitored the timecode information from the projector and determined what frame a subject was viewing when his/her stimulus recognition or TTC response was made. A card for the PC, which read SMPTE timecode, was employed to accomplish this stage of data reduction.

Finally, the site selected for the filming of driving scenes to serve as motion judgment study stimuli was an unopened portion of Route I-476, west of Philadelphia. This site was selected because it was newly paved and provided at least 1 mi (1.6 km) of straight and level roadway for optimal sight distance to the conflict vehicle. Also, because it was not opened to the public, the filming activities did not interfere with traffic flow, and vice versa.

<u>Data Collection Protocol</u>. The first laboratory visit by each subject was devoted to data collection with the large-screen video system. An initial explanation of the study's purpose was given to each participant, after which he/she was seated in the vehicle simulator to receive a further explanation of all relevant controls and displays, i.e., the functions of the steering wheel, the vehicle-mounted CRT tracking task, pedals, and rear-projection screens surrounding the simulator. Sufficient practice was given to each subject to attain a stable level of performance. At the low level of difficulty set for the tracking task, 5 min of practice was typically ample for most subjects.

Referring back to figures 11 and 12, the number of test conditions in which each subject participated was 18 and 9, respectively, for a total of 27 separate trials in the driving simulator. Data collection in the simulator began with the stationary observer block of motion judgment test trials identified in figure 11. These 18 trials represented all combinations of conflict vehicle approach direction and speed, and conflict vehicle separation at the time of the TTC response indicated by the subject. The 18 trials were presented in a different order for all subjects within an age group (i.e, there were 24 presentation orders), using the rapid access capability of the videodisc system to counterbalance for possible effects of fatigue and boredom. Where there were more than 24 subjects in an age group, the remainder were presented with one of the 24 presentation orders previously used. Therefore, anywhere from one to five subjects in an age group received a duplicate trial sequence, due to oversampling of subjects.

For the moving observer block of test trials identified in figure 12, nine trials representing all combinations of conflict vehicle speed and separation at time of response were performed, in a different order of presentation for each subject to counterbalance for effects of fatigue/boredom.

The target vehicle recognition distance-dependent measure was accomplished using a steering wheel-mounted response button. Subjects were instructed to push the button when they could first discern that the object approaching them was in fact a vehicle. The time-to-collision dependent measure was accomplished using a brake pedal response. Each trial was initiated with the subject resting his/her foot on the accelerator pedal. If the trial was a moving observer trial, the subject was asked to begin the concurrent tracking task by pressing the accelerator pedal. Subjects were then given a verbal "ready" signal by the experimenter, after which the scene was presented either on the screen in front of the simulator (for head-on approaches) or on the screen situated at a 90° angle (for a side approach). At some point during the conflict vehicle's approach, the screen went blank. Subjects were asked to imagine that the car was continuing its approach, and to determine at what point the car would hit them if the scene had continued. They were instructed to step on the brake pedal at the moment they estimated the vehicle would collide with their vehicle (the simulator).

The playback system used for presentation of stimuli on all test trials consisted of the Pioneer 8000 videodisc players and a PC computer. The players contained a sync port that allowed for frame-by-frame synchronized playback of the units. Furthermore, the players were equipped with an RS-232 serial port that allowed for two-way communication with the PC, thus permitting the PC to control and monitor the function of the players through a command language they understood, as described earlier in the feasibility study discussion of simulator system interfaces. A predetermined trial sequence was programmed into the PC for each subject. When the experimenter initiated a trial, the PC instructed the players to access the correct scene and play speed, and begin play.

The capability to sync the players with respect to playback speed was especially important to the data collection effort. Wherever varying conflict vehicle speed was indicated in the test conditions described by figures 11 and 12, this effect was achieved at playback of the images in the simulator, not by separately filming the same approach at different speeds. The particular playback speed needed to attain the desired apparent conflict vehicle approach speed during data collection was calculated in relation to the actual vehicle speed during filming: if the speed was 20 mi/h (32 km/h) during filming and playback at apparent speeds of 30, 45, and 60 mi/h (48, 72, and 96 km/h) was desired (see figure 11, for example), then multipliers of 1.5, 2.25, and 3, respectively, were applied to the players' drive speed controllers by the monitoring PC through the serial ports on each player.

At the moment the subject made a TTC response, the PC monitoring simulator instrumentation, in communication with the three videodisc players, recorded the response and queried the players for the frame number at which the response was made. Once the frame number was obtained, the computer compared it to time and distance information stored in a look-up file. The PC had access to files that contained actual time-to-collision values for each frame of all scenes presented for the motion judgment trials.

All of the information describing TTC or distance was displayed to the experimenter after each trial, and was automatically recorded on disc for later input to the Statistical Analysis System (SAS) for data analysis.

At the completion of the 27 large-screen video trials, simple reaction time (RT) was measured for each test subject, so that motor response time could be subtracted from the time-to-collision responses collected in this study, yielding pure decision (judgment time). This would allow comparisons to be made between age groups based entirely on cognitive rather than the integration of cognitive and motor functions, since it is an undisputed finding in the research literature on RT for older persons that behavior slows with age. This measure was obtained by instructing a subject seated in the simulator to rest his/her foot on the accelerator and to attend to the front projection screen that presented a white "1A" on a black background in the center of the screen. The experimenter then gave a verbal "ready" signal, and after a variable amount of time had passed for each trial, the screen went blank. At that point, the subject was to move his/her foot to the brake pedal as quickly as possible, after the "1A" was extinguished. Seven trials were performed, with the fastest and slowest responses discarded from the RT analysis. The average of the five remaining trials of this type determined the simple RT for each subject.

The second visit to the laboratory by each subject was devoted to cinematic and television monitor data collection. Referring back to figures 13 and 14, the numbers of test conditions each subject participated in were 12 and 6, respectively, for a total of 18 trials each for the cinematic and television monitor methodologies, accomplished in the same visit to the laboratory.

Unfortunately, the flexibility in randomizing trial orders afforded by the videodisc technology was not permitted during data collection with the 35mm cinematic methodology. Only one order of presentation of stimuli for trials using "as filmed" conflict vehicle speed trials and only one order of presentation for trials where the conflict vehicle was shown approaching at an increased speed of 60 mi/h (96 km/h) was permitted, since the capability to rapidly and precisely shift to different random locations on a videodisc could not be realized when using a linear image storage/presentation medium (film).

The best, practical means of creating some variation in the order of the presentation of the trials was by dividing laboratory data collection into four blocks:

1. Front windshield target approaches at "as-filmed" speed.

2. Front windshield target "increased speed" approaches.

3. Left side target approaches at "as-filmed" speed.

4. Left side target "increased speed" approaches.

With reference to figures 13 and 14, the specific trials included in block 1 showed head-on approaches of the conflict vehicle at 30 mi/h (48 km/h) for both stationary and moving observers; block 2 included the head-on approaches of the conflict vehicle at 60 mi/h (96 km/h) for both stationary and moving observers; block 3 showed the intersecting vehicle approaches at 30 mi/h (48 km/h) for a stationary observer only; and, the trials included in block 4 showed the intersecting vehicle approaches at 60 mi/h (96 km/h) for a stationary observer only.

Using this scheme of four trial blocks 1 through 4, four different orders of presentation were incorporated into the 35mm cinematic data collection test protocol. In each of the three age groups tested (18-55, 56-74, and 75+ years of age), 6 out of 24 subjects received the same order of presentation of test stimuli: either 1-2-3-4, 4-3-2-1, 2-1-4-3, or 3-4-1-2. Within any given block 1 through 4, the stationary observer trials in a single randomized order for all subjects were presented first, followed by moving observer trials, if any. The same randomized order was applied to trials of each type named above within each block 1 through 4, given the inability to skip around randomly to different locations on the filmtrack.

For trials using the television monitor methodology, all test conditions were accomplished using the same instructions and order of stimulus presentation used in the large-screen video effort already completed. Where trials were omitted in the television monitor methodology, such as the 45 mi/h (72 km/h) approaches of the conflict vehicle, these trials were first eliminated from the large-screen video test protocol stimulus presentation order, and the remaining trials--counterbalanced according to different orders of presentation from subject to subject--were shown in exactly the same sequences.

To achieve one additional level of counterbalancing, during the second laboratory visit, one-half of the overall sample of subjects completed the television measures first, followed by the cinematic measures; the other half of the sample completed the measures using the cinematic methodology first, then the television monitor methodology.

CONTROLLED FIELD STUDY

Objectives. The collection of controlled field data for a limited number of test conditions represented an attempt to empirically validate the time-to-collision (TTC) judgments completed in the laboratory experiments. The objective of this field work was to measure hypothesized age-related differences in motion judgment capabilities from a behind-the-wheel perspective under controlled experimental conditions. An instrumented vehicle was used for this purpose, as described below, and data was collected in a single session for each subject.

Experimental Variables. The motion judgment field study included three independent variables. The independent variables were: (1) the speed of approach of the conflict vehicle, (2) the separation of the conflict vehicle (actual time-to-collision) from the observer at the time of response, and (3) the age (group) of the driver/test subject. These variables are discussed further below. The dependent variable in the field study was each driver's estimated time-to-collision with the conflict vehicle on each test trial.

Safety considerations ruled out field data collection both where a conflict vehicle was separated by only 2.5 s from the observer at the time of response, and all moving observer trials. Thus, only stationary observer test trials where the actual time-to-collision was 5 s and 7 s were performed.

Head-on approaches at 30 and 60 mi/h (48 and 96 km/h) for the conflict vehicle were examined. It may be noted that angle of approach of the conflict vehicle was **not** identified as an independent variable in this study. The test conditions for the field study are described below. Using a repeated-measures design, the same age groups used in the laboratory experiments (18-55, 56-74, and 75+ years of age) defined the levels of the driver age variable in the controlled field study.

Test Conditions. The field test conditions defined by the combinations of independent variables described above are diagrammed in figure 15.

Test Apparatus. The apparatus required for data collection in the field study included an instrumented vehicle, in which the experimenter and one subject at a time rode, plus a conflict vehicle (the white Mercury Marquis driven by a confederate) serving as the target stimulus on each test trial. The primary vehicle instrumentation needs included hardware/ software systems to: (1) record the subject's response for estimated TTC, (2) occlude the subject's vision on motion judgment trials at predetermined (actual) TTC intervals of 5.0 and 7.5 s, and (3) monitor the distance traveled by the conflict vehicle from a known reference point on each trial.

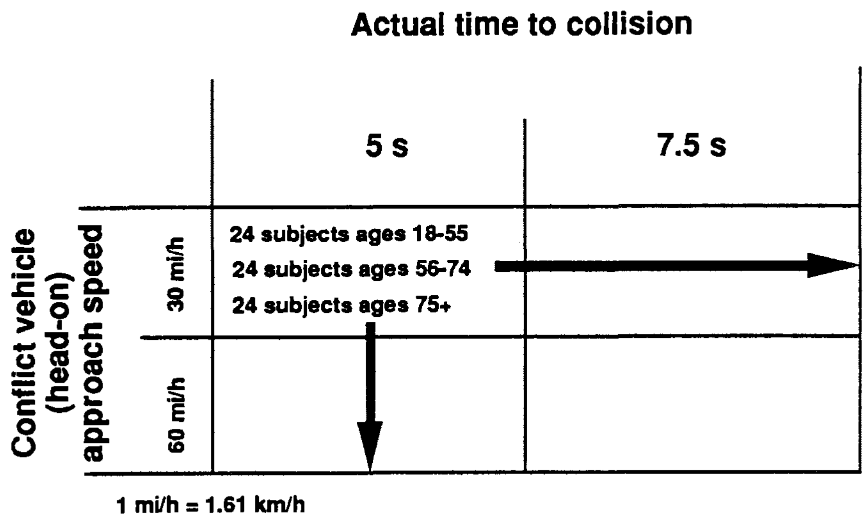


Figure 15. Motion judgment field study test conditions.

Obtaining TTC measurements was accomplished through activation of tape switches mounted on the roadway at distances corresponding to separation times of 5 and 7.5 s, for a vehicle traveling at 30 and 60 mi/h (48 and 96 km/h), respectively, as it approached the subject sitting in the test vehicle. Four tape switches were placed at distances of 220, 330, 440, and 660 ft (67, 100.6, 134, and 201 m) from the test vehicle's position (which remained constant for each trial). As the confederate driving the conflict vehicle crossed (closed) the particular tape switch the computer was monitoring for a particular trial, the occlusion device was triggered to rotate to the full down position, thus blocking the subject's view of the conflict vehicle. The subject then waited for the moment he/she estimated the vehicle would collide with the test vehicle had it maintained its speed and course at the time his/her view became obstructed, and the subject then pressed a hand-held button at the estimated TTC. When the button was pushed, the computer recorded the elapsed time from occlusion onset to button push. The most significant demand this system put on the confederate driver in the conflict vehicle was to ensure that the vehicle was traveling at the correct speed throughout the entire approach, up to and including the time of occlusion.

A conventional, left-side-drive passenger car (mid-size, 4-door sedan) was used for data collection. On all TTC trials, the subject observed the conflict vehicle from the passenger's position in the front seat. As noted above, the conflict vehicle was the same white, full-sized sedan used for filming the laboratory test stimuli. The on-board PC's dedicated to monitoring inputs from the tape switches, recording subjects' responses, and controlling the occlusion device (as required) were the same computers employed in the earlier filming effort.

The occlusion device attached to the ceiling of the instrumented vehicle consisted of two high r/min direct current (DC) motors linked by a common shaft, with a lightweight, opaque visor attached to the shaft. When each trial began, the motors raised and held the visor out of the subject's view. Then, at the appropriate time during the trial, the motors rotated the visor down (through 90°), thus occluding the subject's field of view. The visor was able to rotate from a fully open position to a fully occluded position in less than 1/30 s, in response to a command from the PC monitoring actual TTC on-board the instrumented test vehicle.

Test Stimuli. The field study was conducted on NJ Route 29, just south of Frenchtown. A primary selection criterion for this (in-service) site was low traffic volume with very few intersections along the 2-mi (3.2-km) section; traffic control to restrict entering vehicles was minimal, as one side of the roadway is bordered by the Delaware River. For motion judgment data collection at this site, the instrumented vehicle was parked on the left shoulder of the roadway, facing oncoming traffic. The shoulders at this site were paved, continuous with the road surface, and measured 10 ft (3 m) in width. The conflict (target) vehicle approached head-on, straddling the edgeline, at a speed appropriate for the test trial in progress. Two-way radios were used for communication between the experimenter in the test vehicle and the confederate in the conflict vehicle. Field data collection included four trials (two conflict vehicle approach speeds by two actual time-to-collision separation distances at the time of response). These test conditions were diagrammed earlier in figure 15. The four trial types were presented in a counterbalanced order dictated by a Latin-square design: 1-4-2-3, 2-1-3-4, 3-2-4-1, and 4-3-1-2.

Data Collection Protocol. The test protocol was based upon data collection for one subject at a time in the controlled field study. Subjects were met by the research team at the contractor's office in groups of four, then conveyed by van to the field test site. At the test site, one subject at a time transferred to the instrumented vehicle, performed the required responses, then returned to the van for transport back to the office once all four subjects had responded. Two van loads of subjects per day were accommodated with this approach.

At the beginning of each trial, the experimenter aligned the test (subject's) car on the left shoulder of the roadway; the confederate meanwhile drove approximately 1 mi (1.6 km) away from the test vehicle to the starting position for the conflict vehicle. The conflict vehicle was kept out of sight from the subject sitting in the test vehicle at the beginning of each trial by a curve in the roadway at the conflict vehicle's starting point. The experimenter radioed the confederate when the test vehicle was in place. The confederate then waited for a long gap in the traffic stream to begin the approach toward the instrumented vehicle. Upon sighting the test vehicle, the confederate flashed the headlights to signal to the test subject that this was the vehicle about which the time-to-collision judgment was to be made. The confederate maintained the speed required for the trial during the entire length of the approach. At the appropriate target separation distance for a given trial, the subject's occlusion device dropped before his/her eyes to block the approaching vehicle from sight. The subject was then required to mentally calculate the point at which the conflict vehicle would collide with him/her, if the vehicle maintained a head-on course, and to push the hand-held response button at the precise moment of the estimated collision.

RESULTS AND DISCUSSION

Results. Results for the motion judgment experiments, where subjects viewed oncoming vehicle targets and estimated the time-to-collision (TTC) after the target was removed from view, are presented below. The results for a secondary dependent variable, target recognition distance, are also presented. In all cases, individual differences in simple reaction time (RT) to perform the button-push responses for these dependent measures have been factored out.

The following data report mean study results for all four different stimulus presentation formats: three laboratory simulation techniques, plus controlled field trials using an instrumented vehicle. The laboratory stimulus presentation formats included large-screen projection video, 20-in (51-cm) television monitor, and (large-screen) 35mm cinematic projection.

Complete sets of figures will display the results in each task by subject age group and target vehicle approach speed, for both the primary and secondary dependent measures. For figures displaying TTC results in this section, calculated values indicating the virtual distance of the target vehicle at the mean TTC for each group are also shown. This informs the reader of the point in the target vehicle's approach it would have reached at the time of the (mean) TTC response for each group.

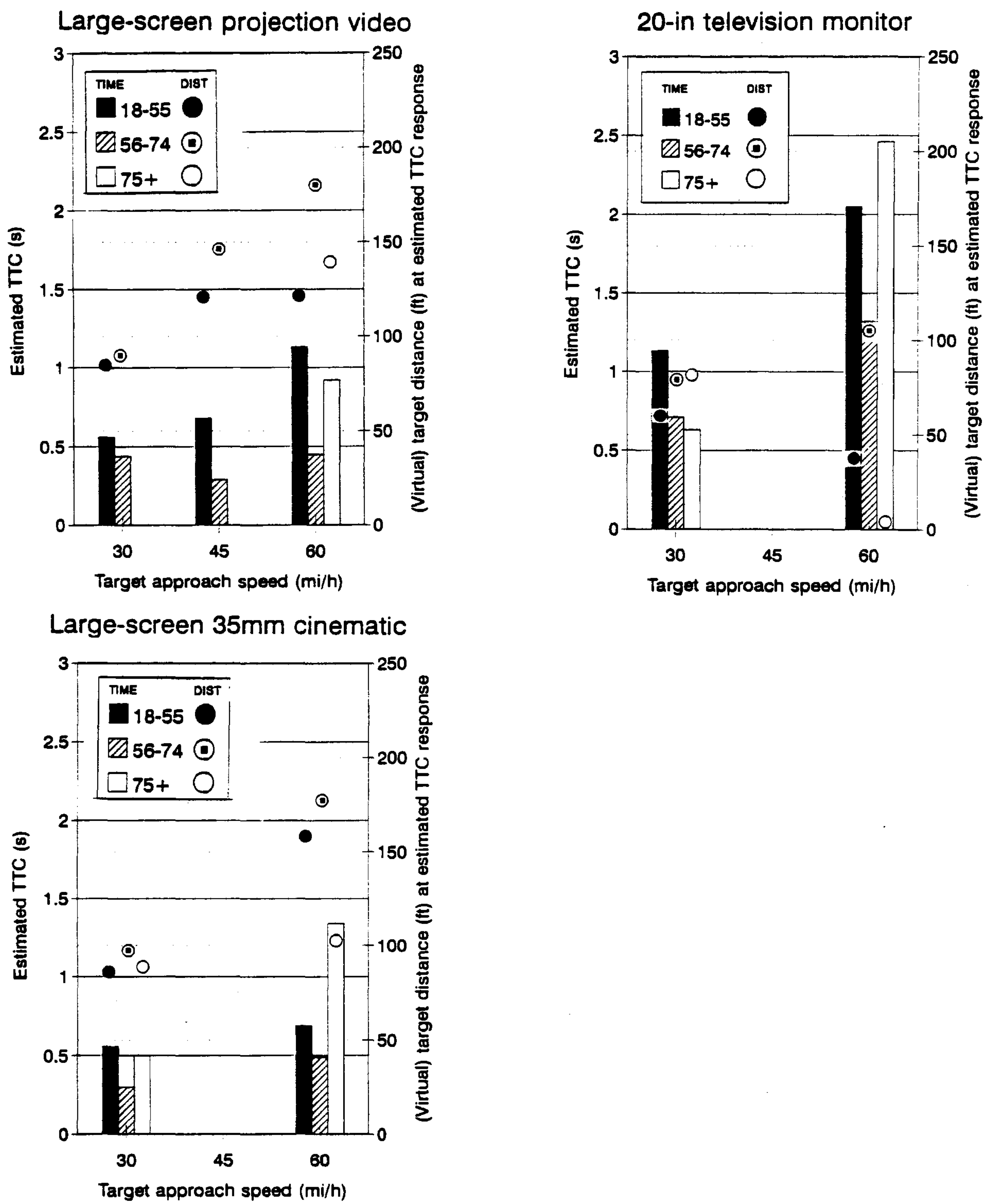
Results for each of the stimulus presentation formats are also presented in appendix B in the form of tables of descriptive statistics for a unique set of test conditions as defined by subject age and by combinations of the other included independent variables: stationary vs. moving observer, head-on vs. side (90°) target vehicle approach direction, and varying target vehicle approach speed. The descriptive statistics are always presented such that results for the primary dependent measure (estimated TTC) and the secondary dependent measure (target recognition distance) appear in the same table.

Accompanying text will discuss findings summarized in the figures and tables, and will report the results of inferential statistical tests of the observed differences. The analysis technique applied to these data was the General Linear Models Procedure (PROC GLM) in the Statistical Analysis System (SAS) (release 6.02). Age group, target speed, and target approach direction were identified as independent variables in the GLM model statement in these analyses; analyses were blocked according to stimulus presentation methodology, stationary-vs.-moving observer status, and actual TTC. Due to the included repeated measures in the research design for this study, the potential effects of subject age group were evaluated using mean square subjects within group [SN(GRP)] as the error term. For all tests using GLM, the type III (vs. type I) sums of squares terms were selected for calculation of F values (i.e., the analysis output value that is tested for statistical significance). **All of the actual F-tables produced as GLM output have been deferred to appendix C.**

The estimated TTC results for stationary observers viewing a head-on target approach with actual TTC = 2.5 s, 5.0 s, and 7.5 s are summarized in figures 16, 18, and 20. Figures 17, 19, and 21 present the target recognition distance results for these same test conditions. The corresponding descriptive statistics in appendix B, organized according to stimulus display type, are reported for the large-screen video projection methodology in table 13, for the television monitor methodology in table 14, for the 35mm cinematic methodology in table 15, and for the controlled field methodology (estimated TTC results for actual TTC = 5.0 s and 7.5 s only) in table 16.

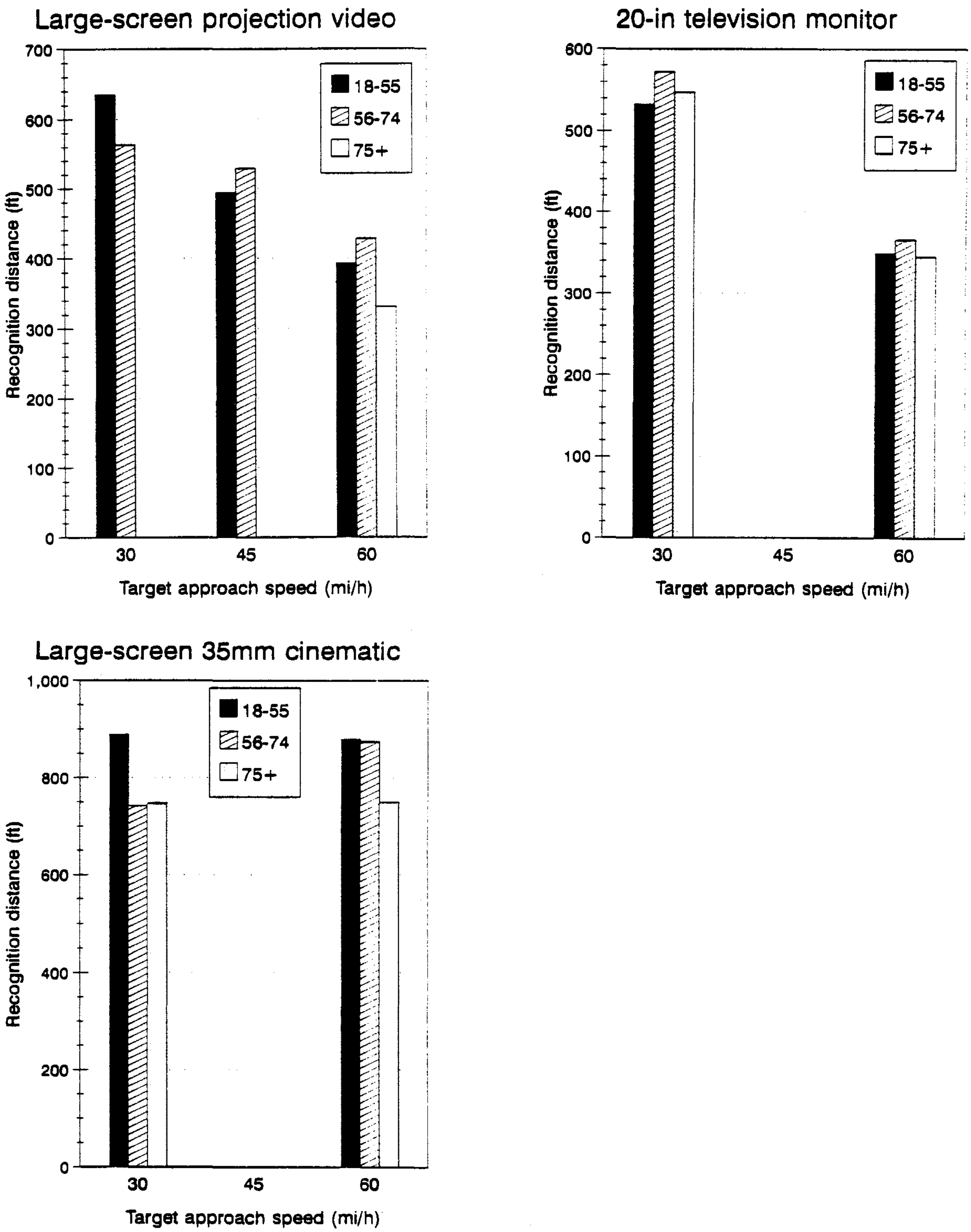
Next, figures 22, 24, and 26 summarize the estimated TTC results for stationary observers viewing a 90° target approach with actual TTC = 2.5 s, 5.0 s, and 7.5 s, while figures 23, 25, and 27 present the target recognition distance results for these same conditions. The corresponding descriptive statistics in appendix B are reported for the large-screen video projection methodology in table 17, for the television monitor methodology in table 18, and for the 35mm cinematic methodology in table 19. No controlled field trials were performed for these test conditions.

Estimated TTC results for moving observers viewing a head-on target approach with actual TTC = 2.5 s, 5.0 s, and 7.5 s are summarized in figures 28, 30, and 32. Figures 29, 31, and 33 show the target recognition distance results for these test conditions. The corresponding descriptive statistics in appendix B are reported for the large-screen video projection methodology in table 20, for the television monitor methodology in table 21, and for the 35mm cinematic methodology in table 22.



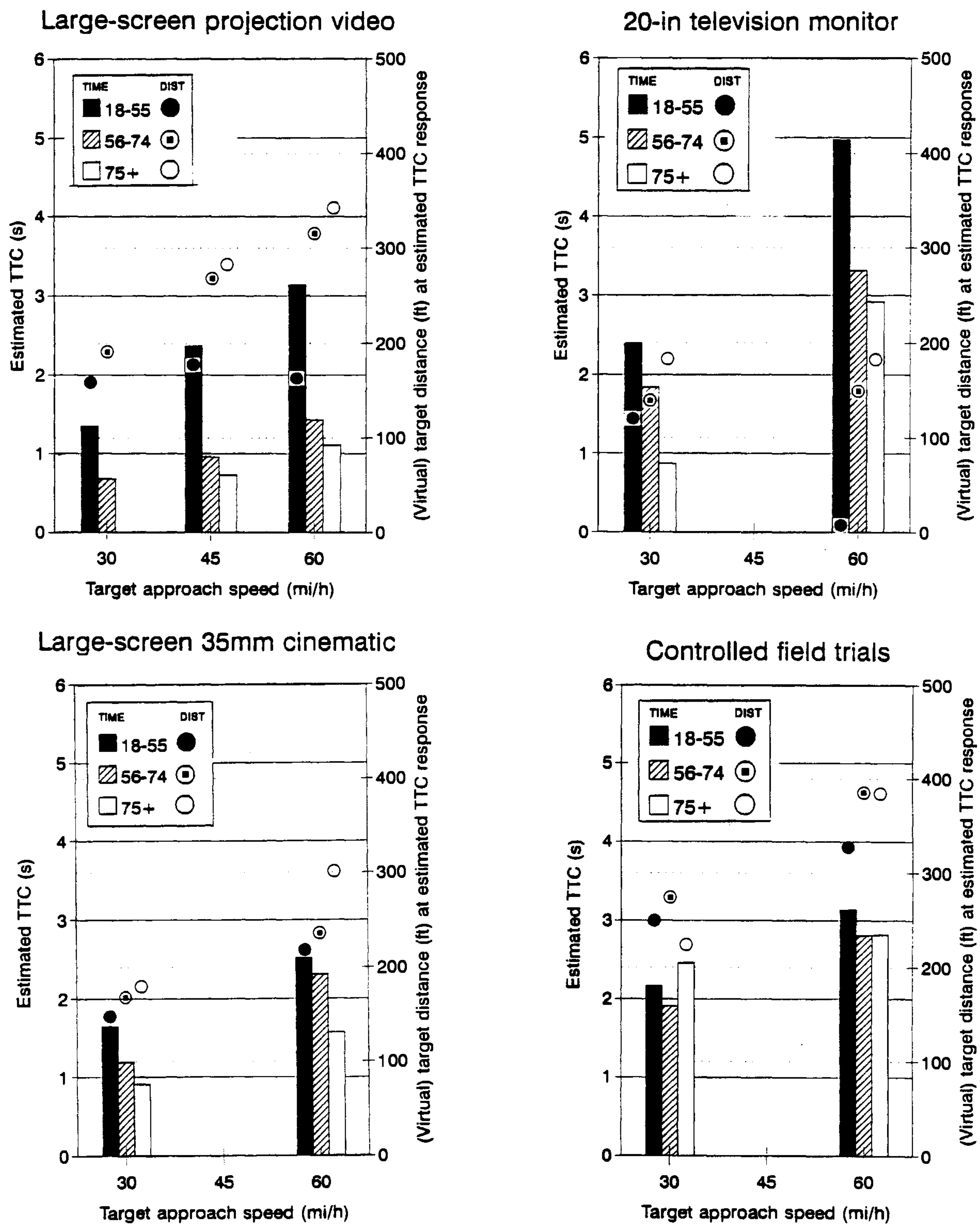
1 mi/h = 1.61 km/h
1 ft = 0.305 m

Figure 16. Estimated TTC for stationary observers in three age groups, for a vehicle approaching head-on with actual TTC = 2.5 s.



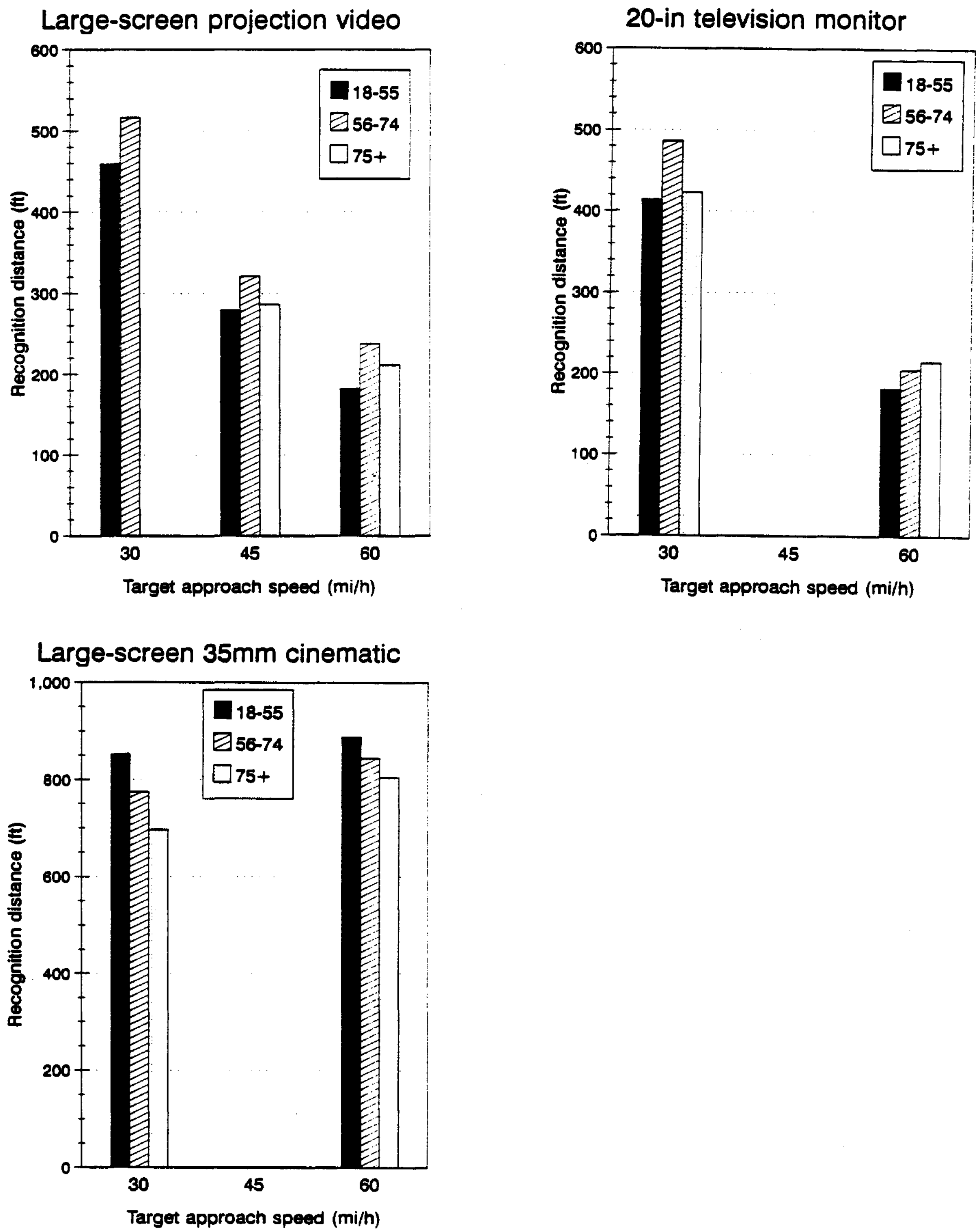
1 mi/h = 1.61 km/h
1 ft = 0.305 m

Figure 17. Target recognition distance (ft) for stationary observers in three age groups, for a vehicle approaching head-on with actual TTC = 2.5 s.



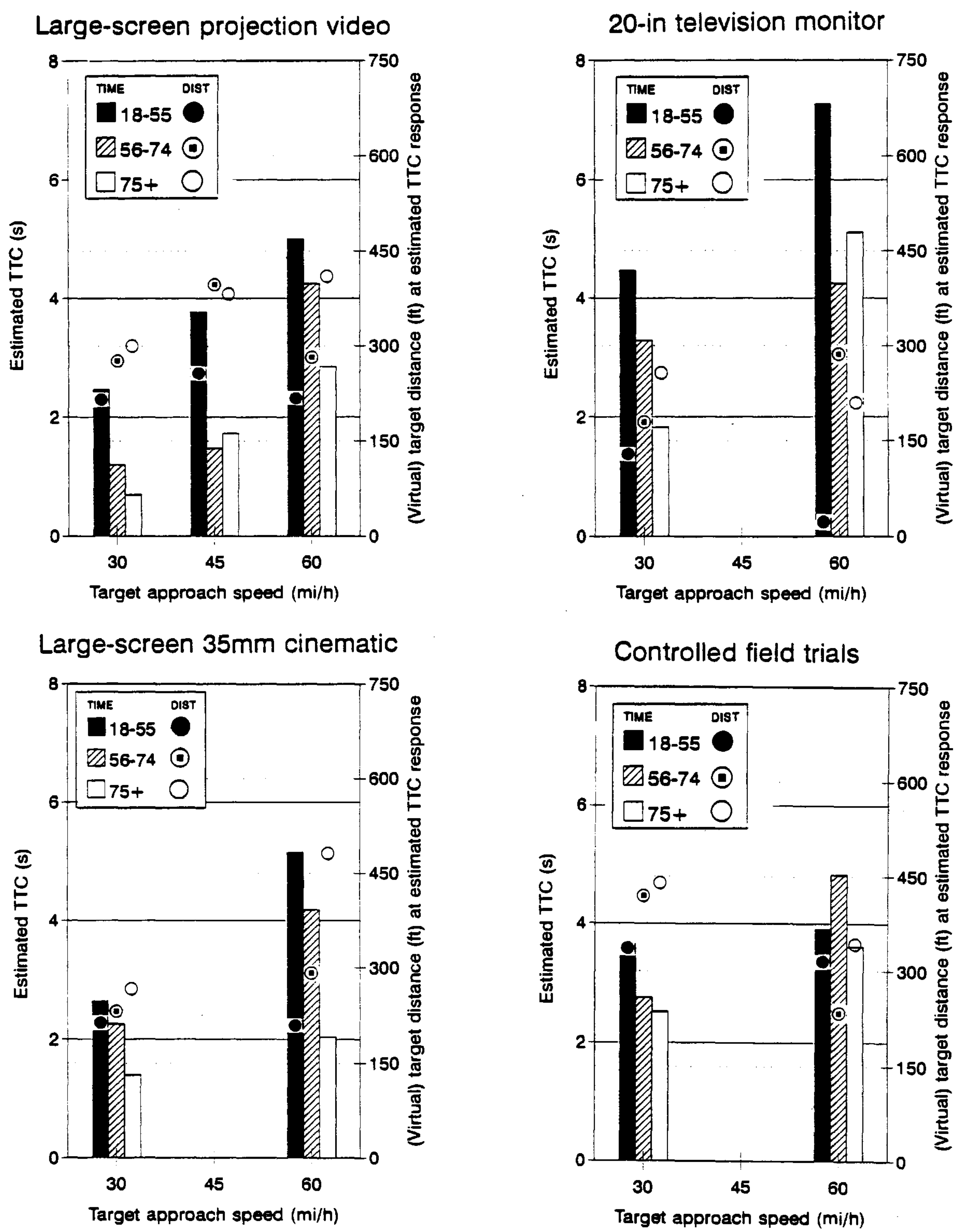
1 mi/h = 1.61 km/h
1 ft = 0.305 m

Figure 18. Estimated TTC for stationary observers in three age groups, for a vehicle approaching head-on with actual TTC = 5.0 s.



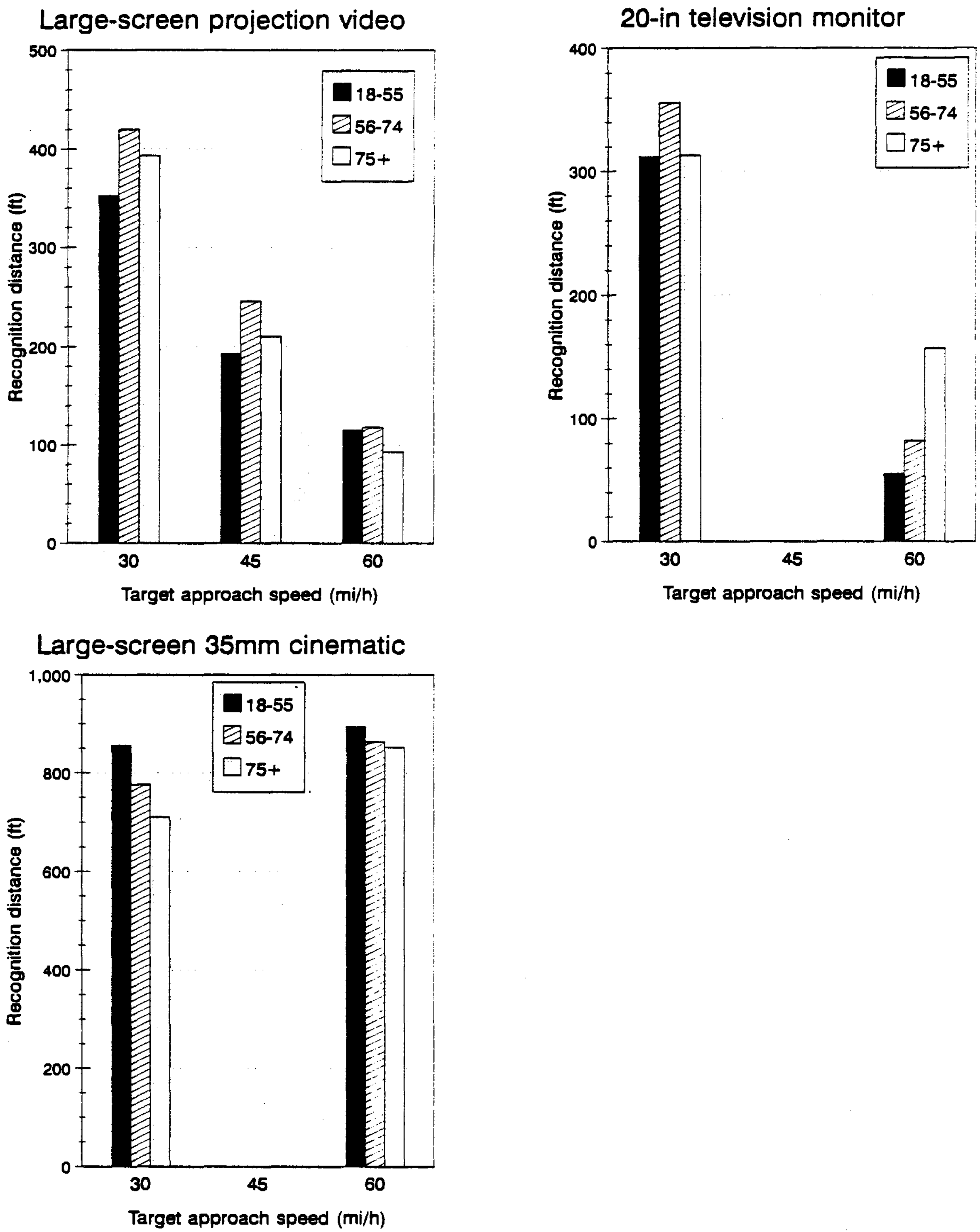
1 mi/h = 1.61 km/h
1 ft = 0.305 m

Figure 19. Target recognition distance (ft) for stationary observers in three age groups, for a vehicle approaching head-on with actual TTC = 5.0 s.



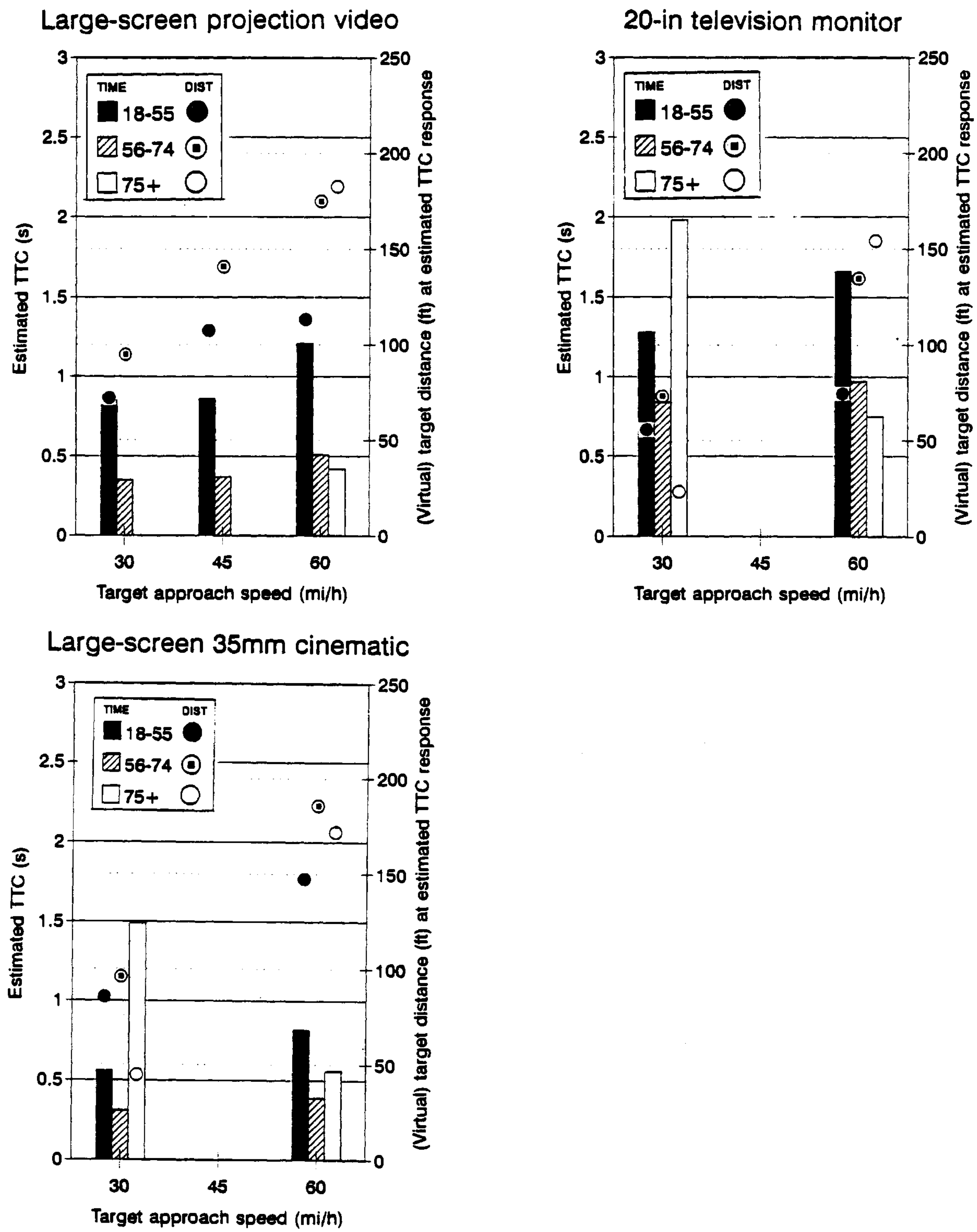
1 mi/h = 1.61 km/h
1 ft = 0.305 m

Figure 20. Estimated TTC for stationary observers in three age groups, for a vehicle approaching head-on with actual TTC = 7.5 s.



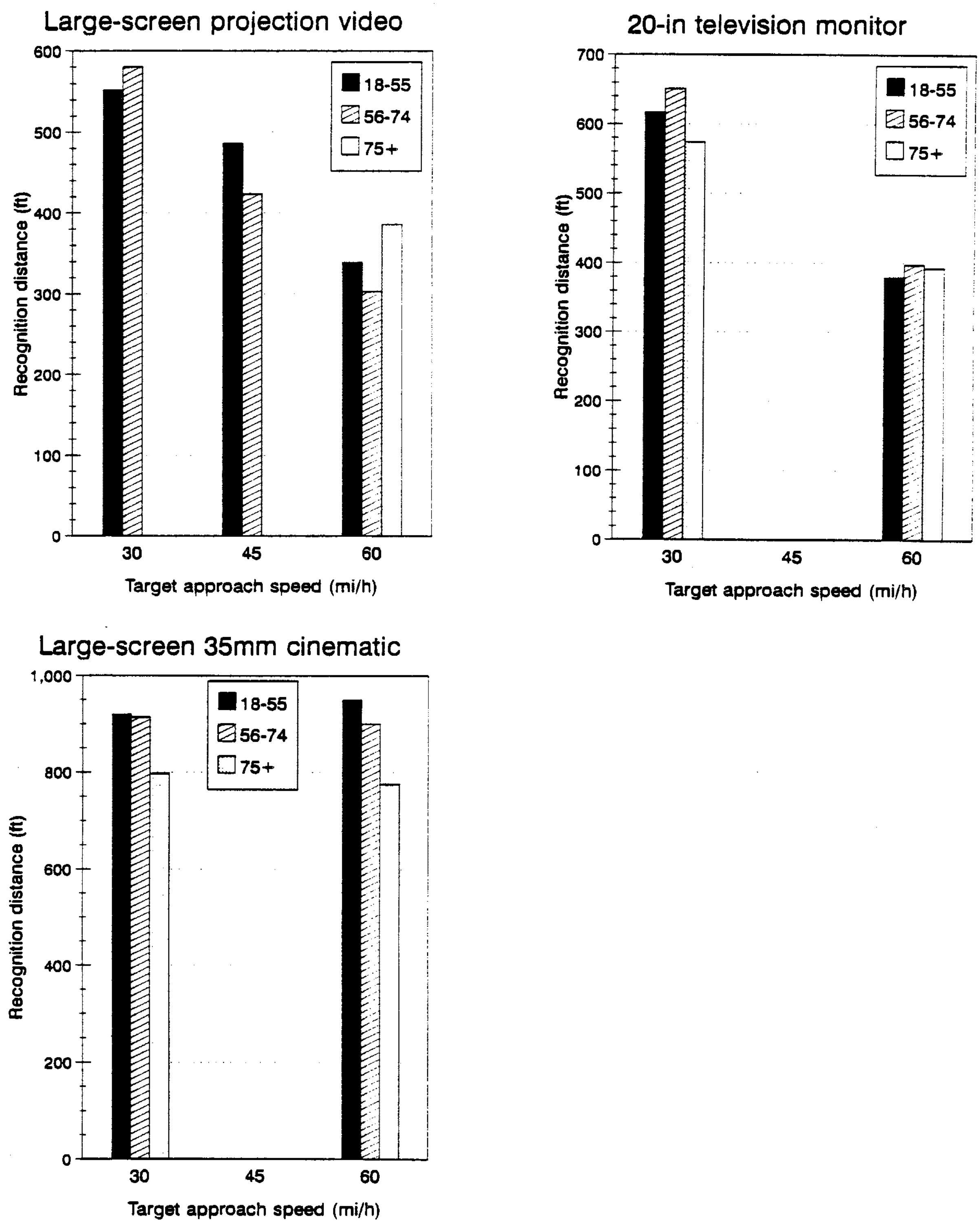
1 mi/h = 1.61 km/h
1 ft = 0.305 m

Figure 21. Target recognition distance (ft) for stationary observers in three age groups, for a vehicle approaching head-on with actual TTC = 7.5 s.



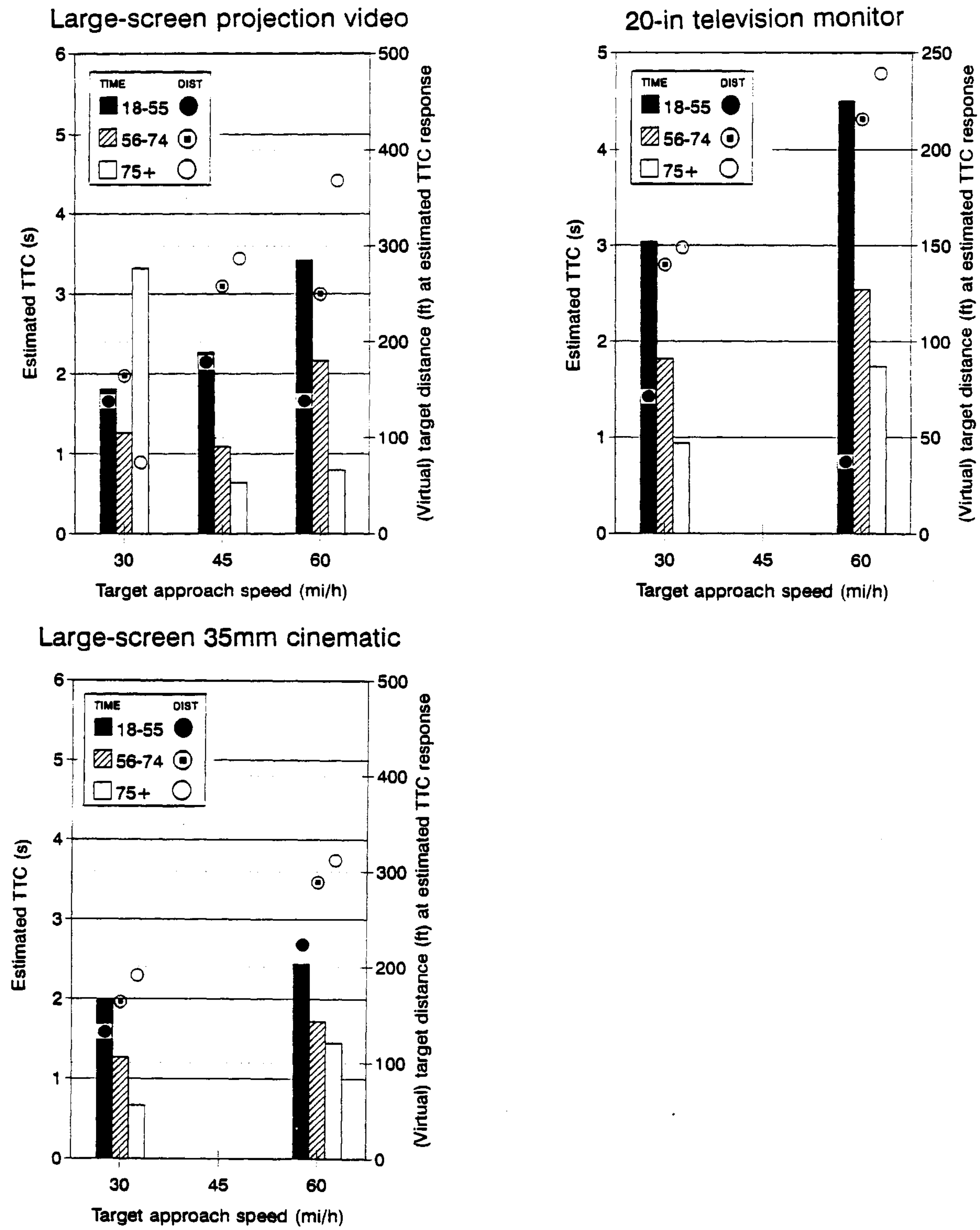
1 mi/h = 1.61 km/h
1 ft = 0.305 m

Figure 22. Estimated TTC for stationary observers in three age groups, for a vehicle approaching from 90° with actual TTC = 2.5 s.



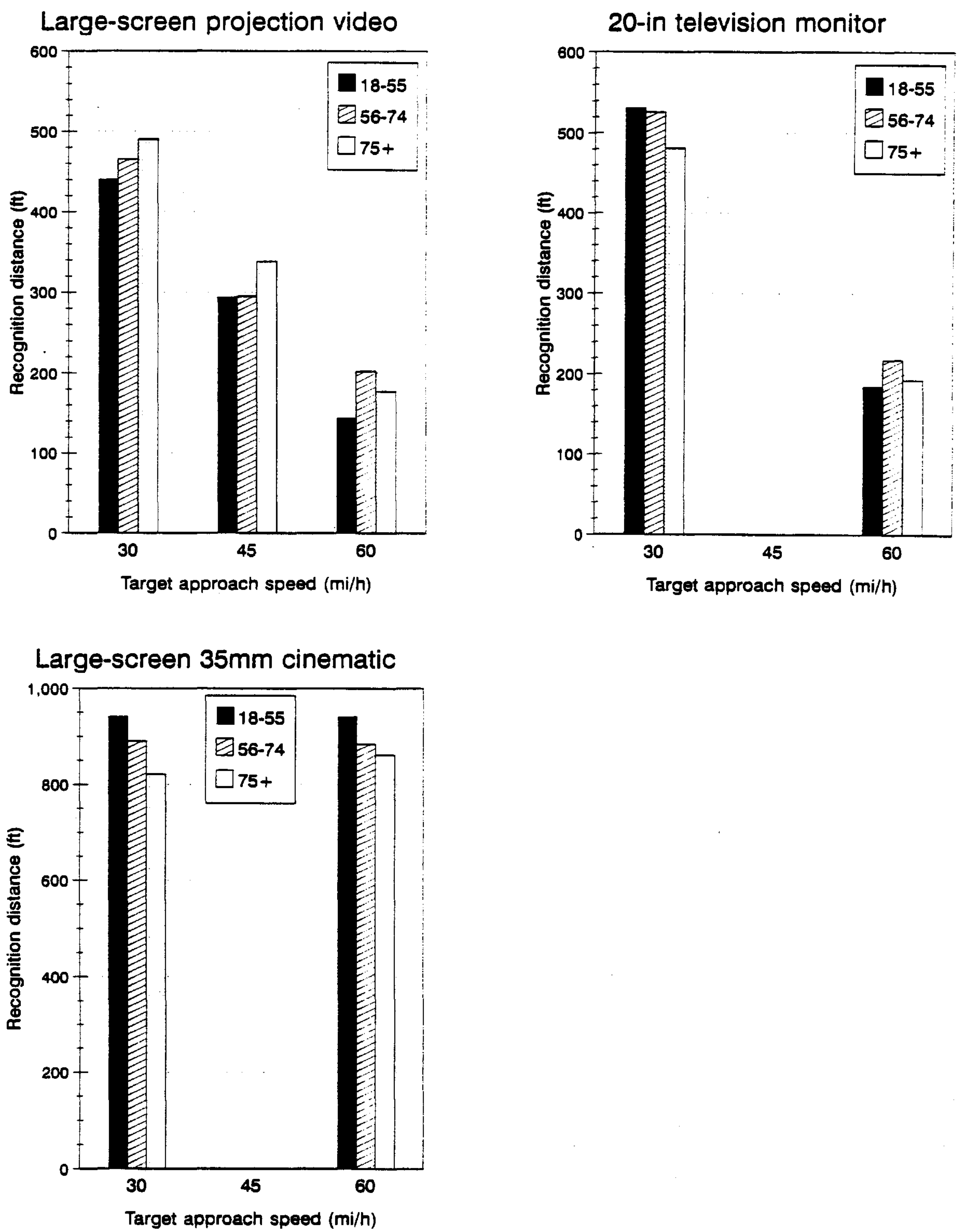
1 mi/h = 1.61 km/h
1 ft = 0.305 m

Figure 23. Target recognition distance (ft) for stationary observers in three age groups, for a vehicle approaching from 90° with actual TTC = 2.5 s.



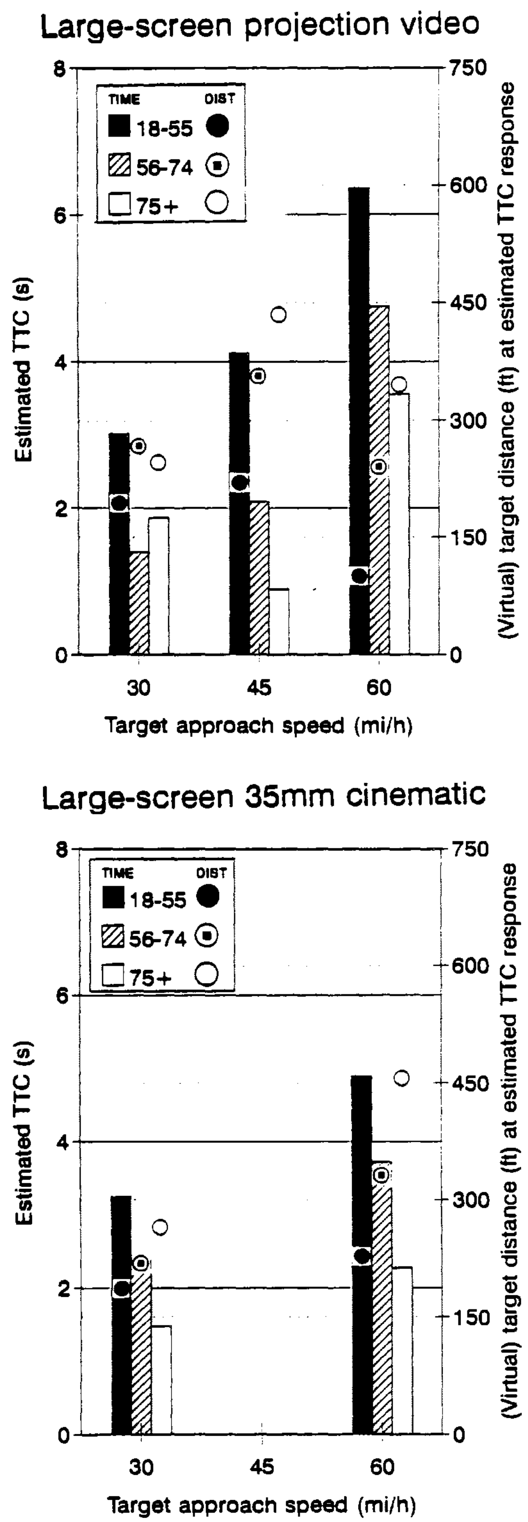
1 mi/h = 1.61 km/h
1 ft = 0.305 m

Figure 24. Estimated TTC for stationary observers in three age groups, for a vehicle approaching from 90° with actual TTC = 5.0 s.



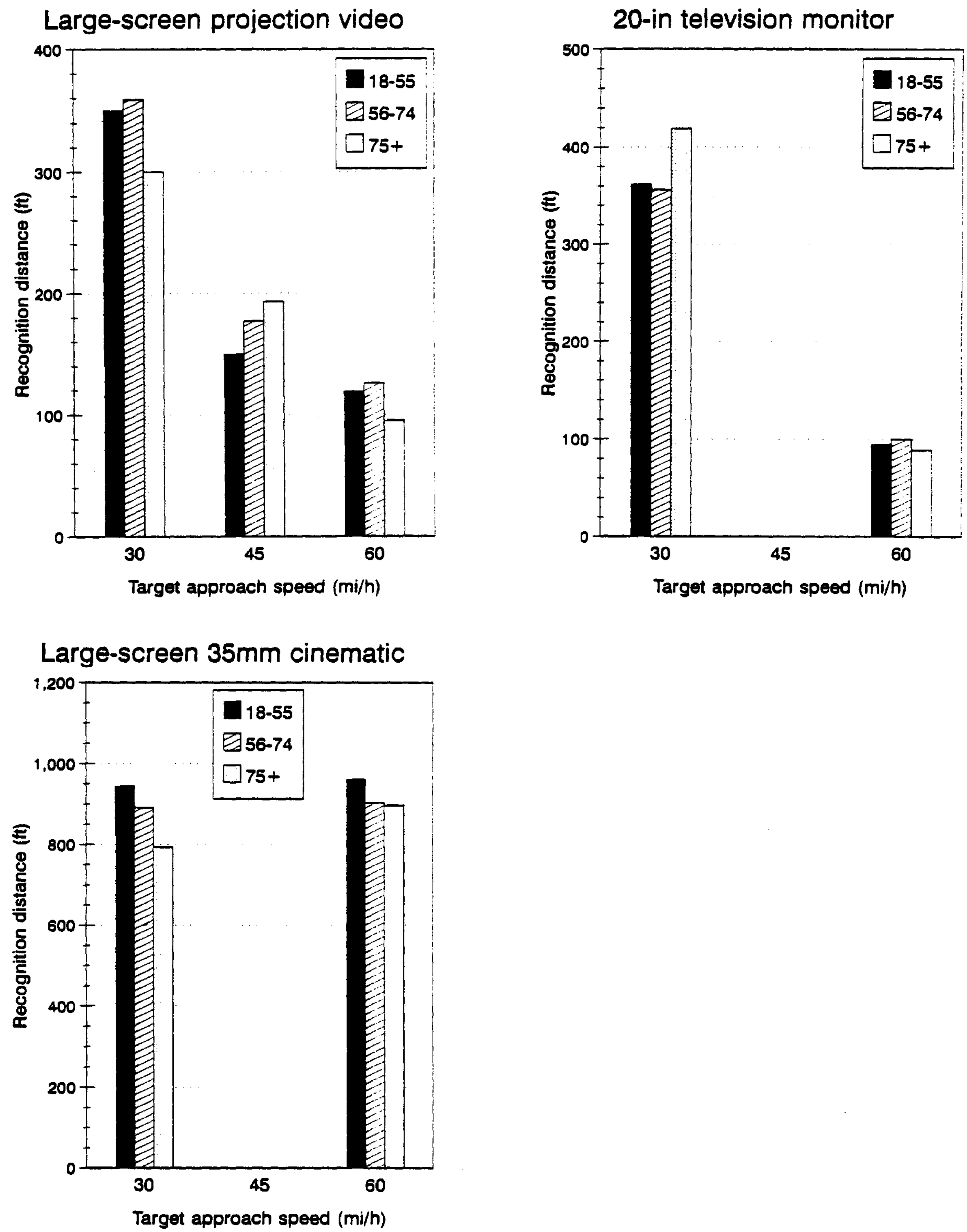
1 mi/h = 1.61 km/h
1 ft = 0.305 m

Figure 25. Target recognition distance (ft) for stationary observers in three age groups, for a vehicle approaching from 90° with actual TTC = 5.0 s.



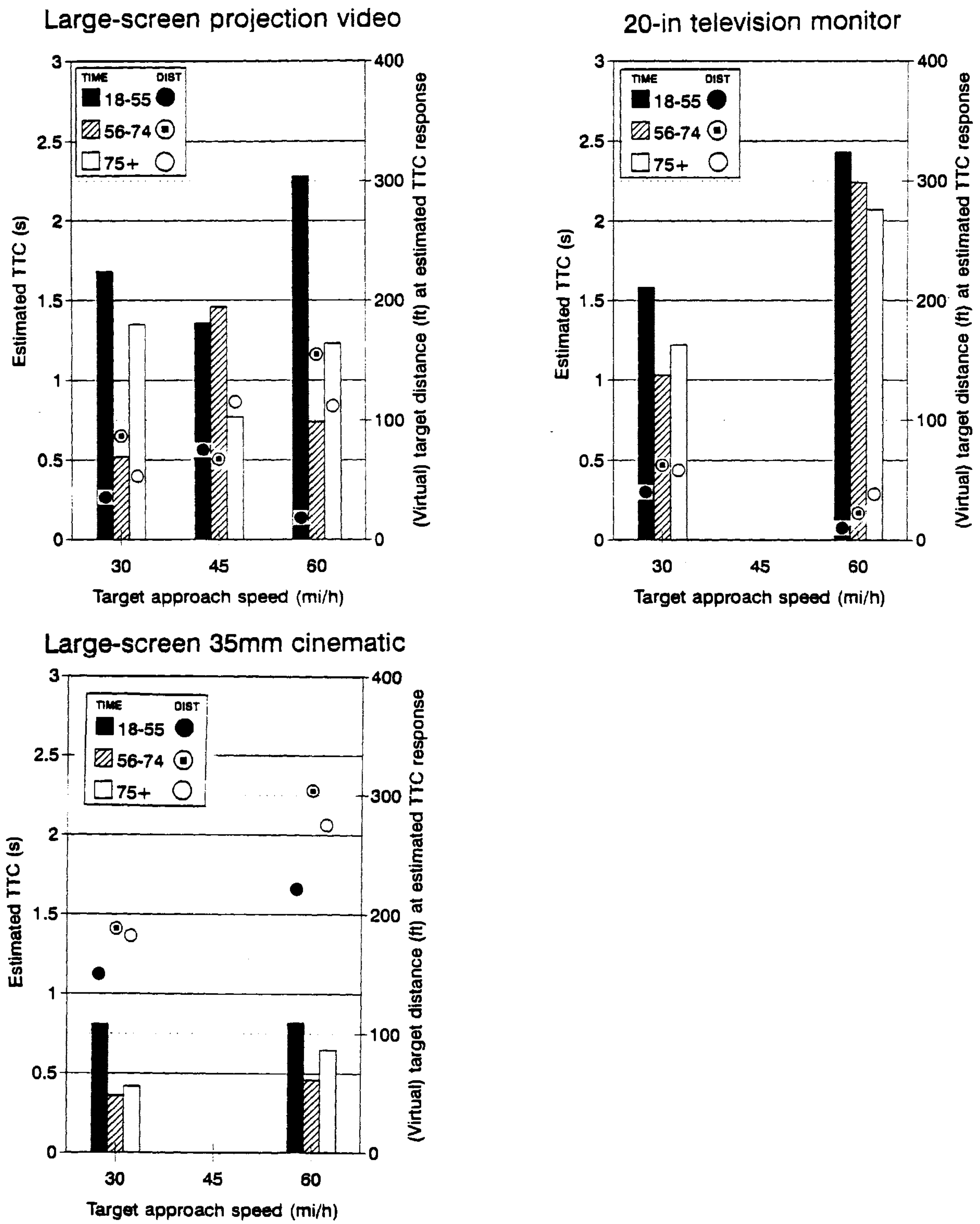
1 mi/h = 1.61 km/h
1 ft = 0.305 m

Figure 26. Estimated TTC for stationary observers in three age groups, for a vehicle approaching from 90° with actual TTC = 7.5 s.



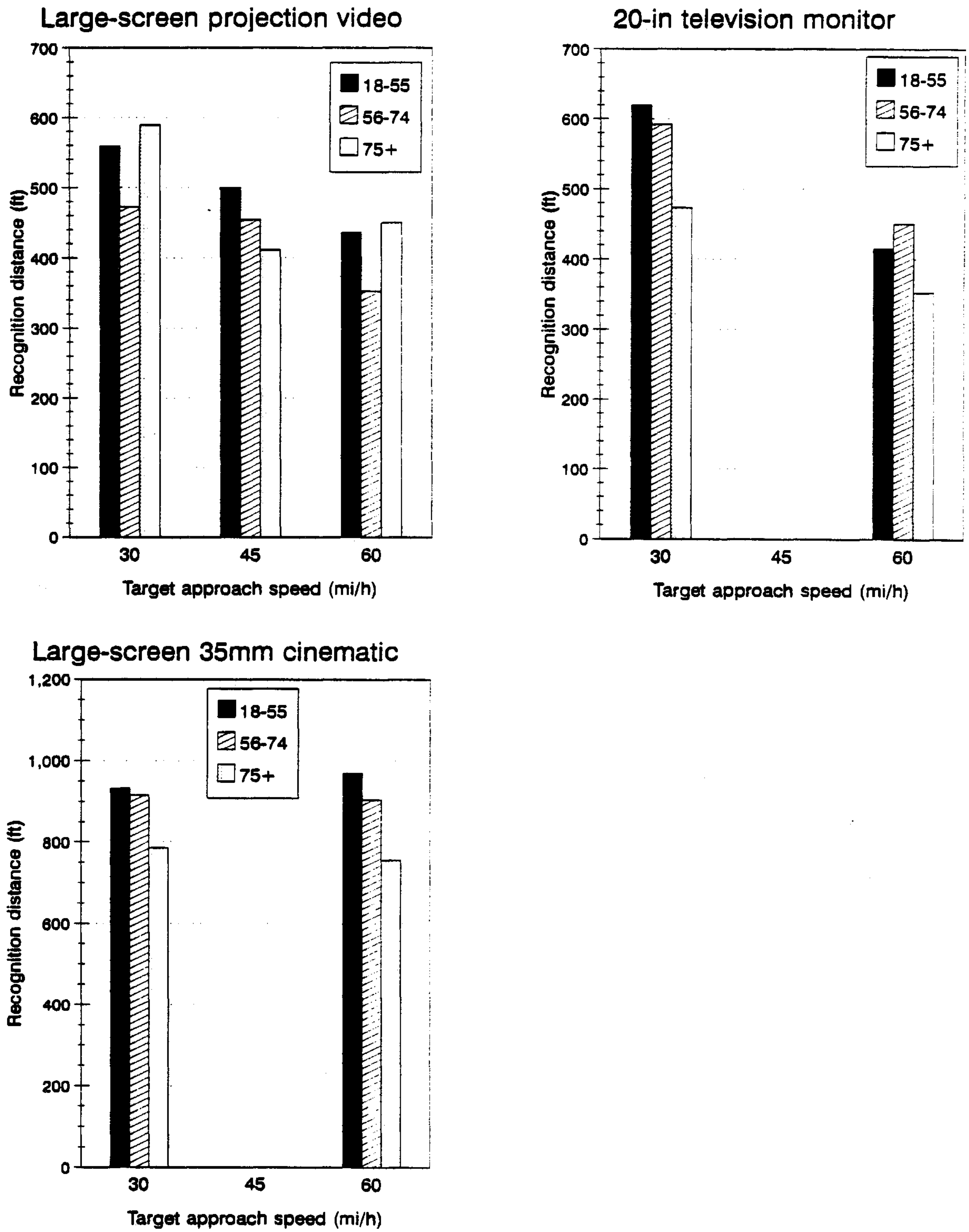
1 mi/h = 1.61 km/h
1 ft = 0.305 m

Figure 27. Target recognition distance (ft) for stationary observers in three age groups, for a vehicle approaching from 90° with actual TTC = 7.5 s.



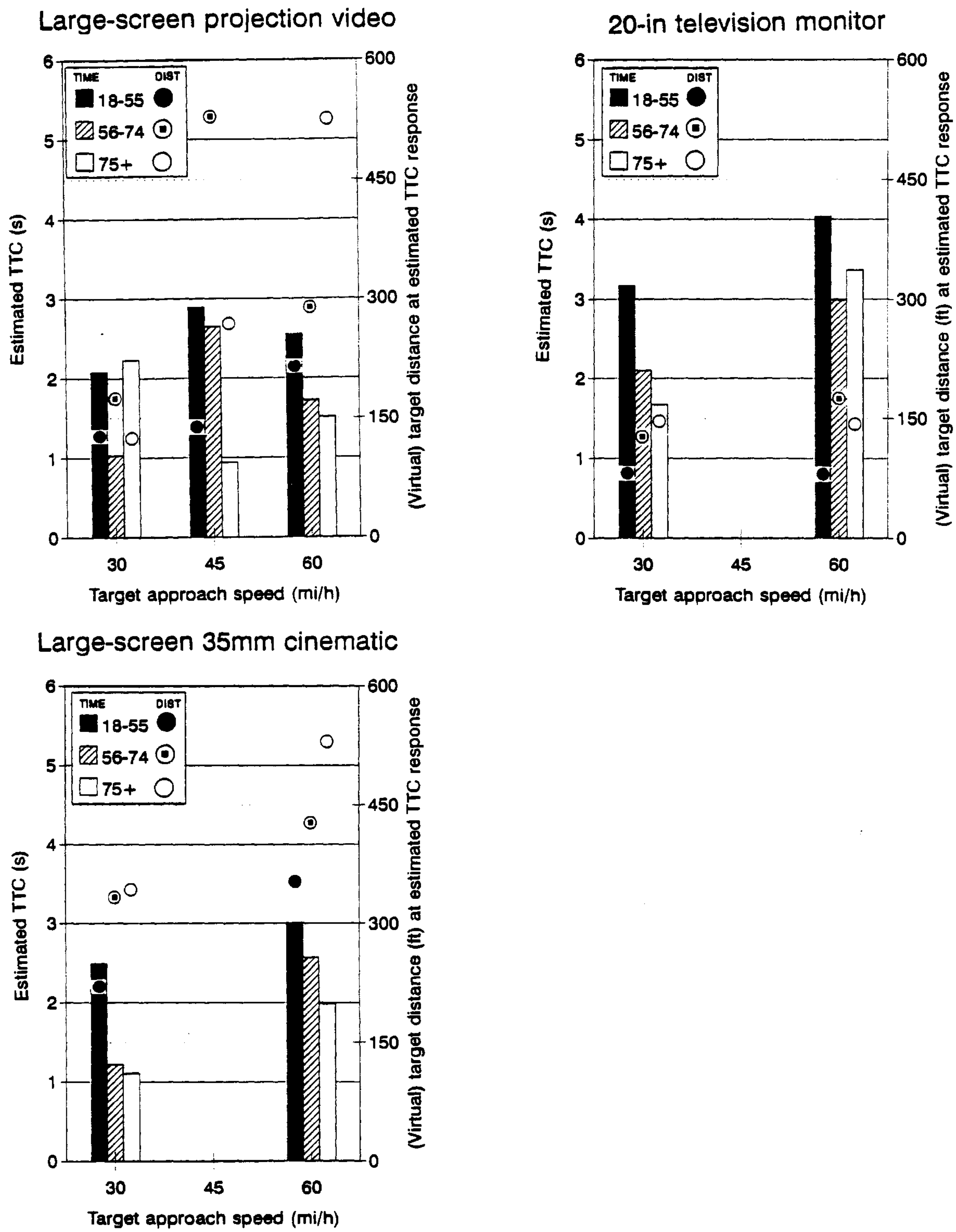
1 mi/h = 1.61 km/h
1 ft = 0.305 m

Figure 28. Estimated TTC for moving observers in three age groups, for a vehicle approaching head-on with actual TTC = 2.5 s.



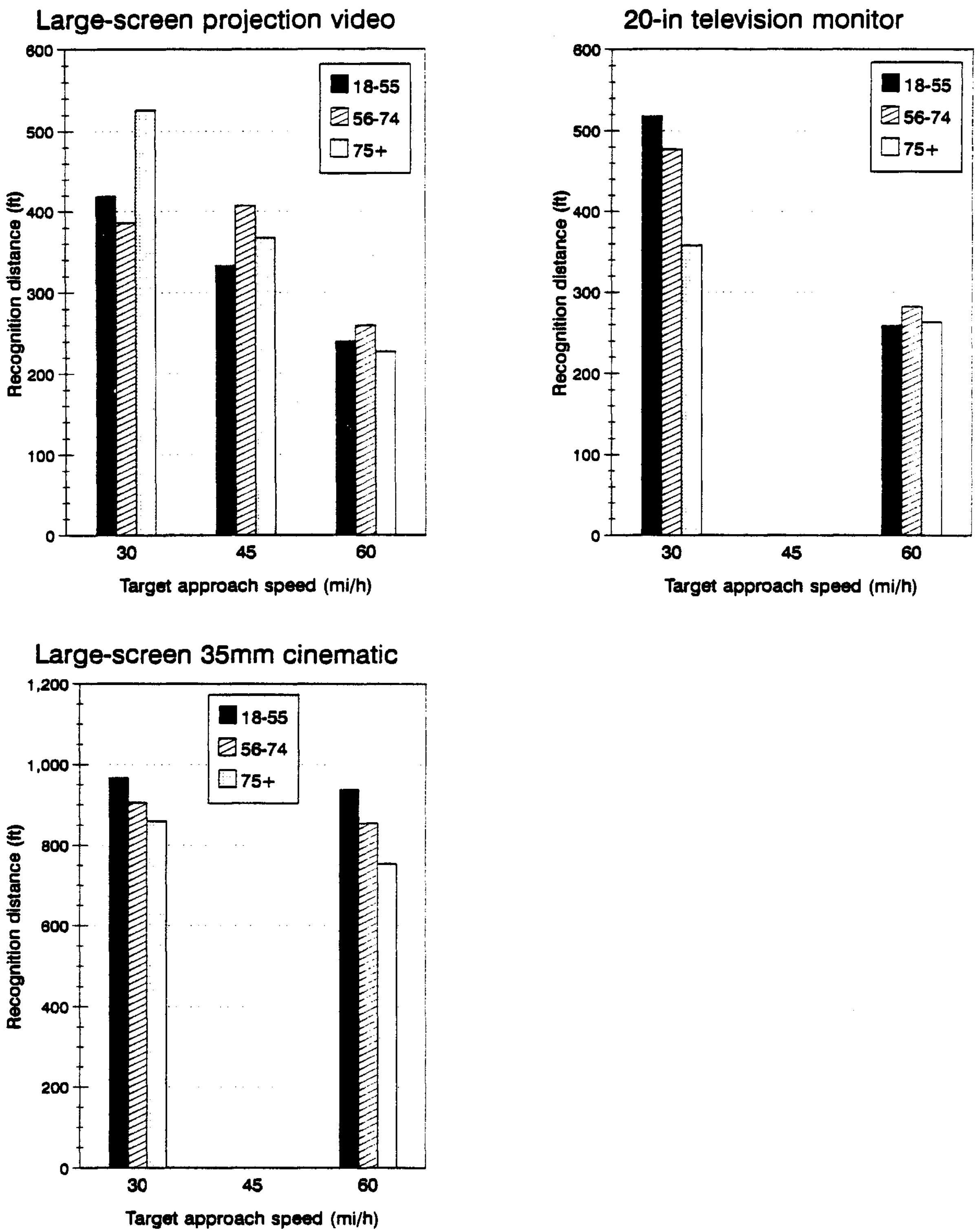
1 mi/h = 1.61 km/h
1 ft = 0.305 m

Figure 29. Target recognition distance (ft) for moving observers in three age groups, for a vehicle approaching head-on with actual TTC = 2.5 s.



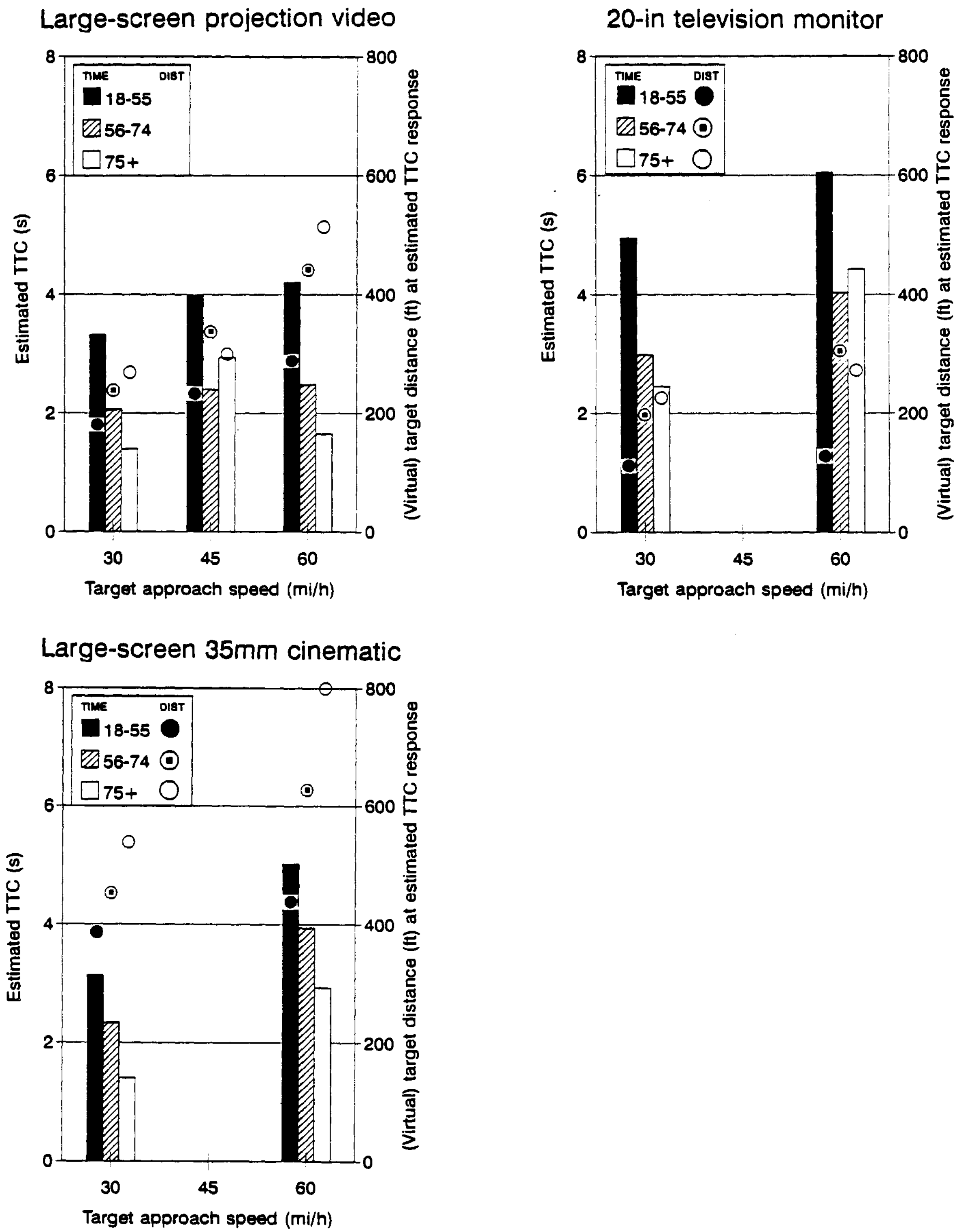
1 mi/h = 1.61 km/h
1 ft = 0.305 m

Figure 30. Estimated TTC for <u>moving</u> observers in three age groups, for a vehicle approaching <u>head-on</u> with actual TTC = <u>5.0</u> s.



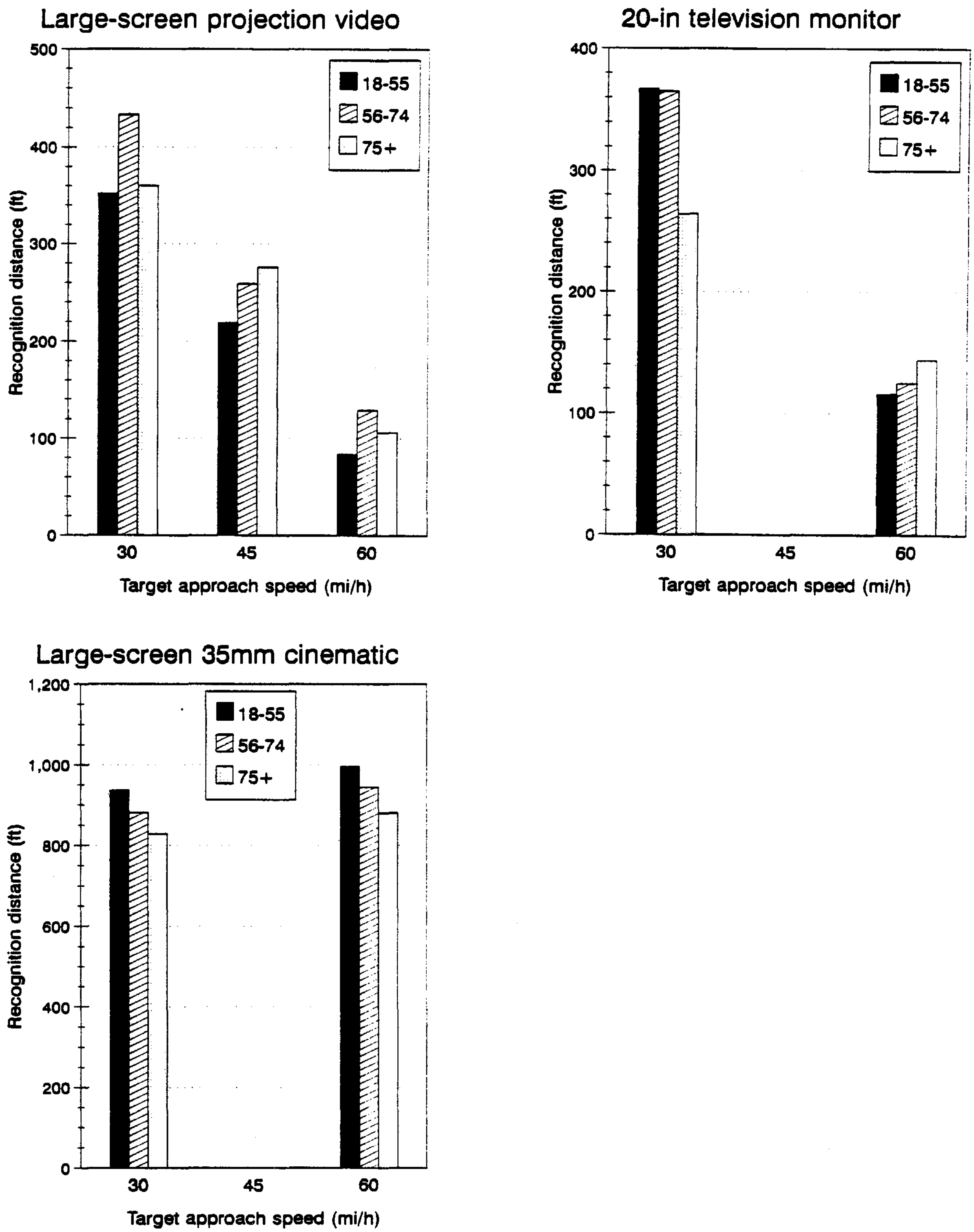
1 mi/h = 1.61 km/h
1 ft = 0.305 m

Figure 31. Target recognition distance (ft) for <u>moving</u> observers in three age groups, for a vehicle approaching <u>head-on</u> with actual TTC = <u>5.0</u> s.



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

Figure 32. Estimated TTC for moving observers in three age groups, for a vehicle approaching head-on with actual TTC = 7.5 s.



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

Figure 33. Target recognition distance (ft) for <u>moving</u> observers in three age groups, for a vehicle approaching <u>head-on</u> with actual TTC = <u>7.5</u> s.

As noted above, these figures associate each mean estimated TTC response denoted by the bar graphs with a corresponding distance value--the distance of the target vehicle from the observer that it would have reached during its approach, at the estimated TTC for a given group. Since **underestimation** of TTC was consistently demonstrated in this study, these virtual distance values are always greater than zero.

Analyses of performance differences for significant effects and interactions began with the stationary observer conditions, where a significant effect of age group where actual TTC = 2.5 s was demonstrated only for target recognition distance, and only with cinematic stimulus presentation ($F=9.48$; $df=2$; $p<.0003$). This effect revealed that increasing age resulted in shorter target recognition distances.

The most commonly observed effect on stationary observer trials with an actual TTC = 2.5 s was that of target speed. This main effect was demonstrated for video projection and television monitor formats, on both estimated TTC and target recognition distance; for these stimulus display methodologies estimated TTC increased, while recognition distance **decreased**, with increasing target vehicle speed. The effect of target speed on estimated TTC using video projection was indicated by an $F=10.41$ ($df=2$; $p<.0001$) and on recognition distance by $F=26.77$ ($df=2$; $p<.0001$). The effect of target speed on estimated TTC when the television monitors were used to display test stimuli was indicated by an $F=6.16$ ($df=1$; $p<.01$) and the effect on recognition distance was indicated by $F=284.74$ ($df=1$; $p<.0001$). Interestingly, no effects of this variable were demonstrated using the cinematic display methodology when actual TTC = 2.5 s.

The other independent variable examined in these tests for stationary observers with an actual TTC = 2.5 s was target approach direction. No significant effects on estimated TTC of this variable were found, under any stimulus presentation method. Significant effects on target recognition distance were shown using television monitor stimulus presentation ($F=15.26$; $df=1$; $p<.0001$) and cinematic presentation ($F=26.81$; $df=1$; $p<.0001$); these effects represented a modest lengthening of recognition distances for intersecting (90°) vs. head-on targets.

Three, isolated two-way interactions were demonstrated in the stationary observer, 2.5-s actual TTC analyses. In each case, the effect was on estimated TTC, not recognition distance. An age-group-by-target speed interaction was indicated for the video projection data ($F=7.79$; $df=4$; $p<.0001$). An age-group-by-target approach direction interaction was indicated, also for the video projection data ($F=5.29$; $df=2$; $p<.006$). And, a target-speed-by-target approach direction interaction was indicated for the television monitor data ($F=12.75$; $df=1$; $p<.0004$).

One three-way interaction--age group by target speed by target approach direction--was found for each laboratory methodology as well. This effect was demonstrated for the video projection data on target recognition distance ($F=2.89$; $df=3$; $p<.04$), and on estimated TTC for the television monitor data ($F=5.22$; $df=2$; $p<.006$) and the cinematic projection data ($F=3.17$; $df=2$; $p<.05$).

Overall, it is important to note that the majority of missing cells in the General Linear Model (GLM) analyses (i.e., fewer than five valid responses per cell) occurred when actual TTC = 2.5 s (see tables 13 and 17 in appendix B).

The next set of data analyses pertained to stationary observer trials where actual TTC = 5.0 s. As described in table 16, these conditions also included data collected in the field, though only at two target approach speeds [30 and 60 mi/h (48 and 72 km/h)] and one target approach direction (head-on).

Significant effects of age group on estimated TTC under these conditions were demonstrated using video projection ($F=4.21$; $df=2$; $p<.02$), television monitor ($F=10.25$; $df=2$; $p<.0001$), and cinematic ($F=6.40$; $df=2$; $p<.003$) stimulus presentation, but not in the controlled field trials. The typical pattern across all laboratory methodologies was decreasing TTC estimates with increasing subject age. The same effect of age group on target recognition distance was found only for cinematic stimulus presentation among the various laboratory display methods ($F=8.29$; $df=2$; $p<.0006$).

The most commonly demonstrated effect under stationary observer conditions with actual TTC = 5.0 s was that of target speed. As a general rule, target recognition distances decreased and estimated TTC increased, with increasing target speed. An exception was noted under cinematic stimulus presentation, where recognition distance improved somewhat at higher target speeds, particularly for the oldest subjects. The GLM tests of the target speed effect on estimated TTC yielded $F=10.07$ ($df=2$; $p<.0001$) using video projection, $F=67.71$ ($df=1$; $p<.0001$) using television monitor, and $F=95.18$ ($df=1$; $p<.0001$) using cinematic methodologies. In the controlled field trials, the effect of target speed on estimated TTC was indicated by $F=11.83$ ($df=1$; $p<.0013$).

The effect of target approach direction, with a stationary observer and actual TTC = 5.0 s, was significant in three instances. For video projection stimulus presentation only, this variable significantly influenced estimated TTC ($F=5.99$; $df=1$; $p<.02$), though this result could be attributed to an anomalously high value for the oldest group of subjects when the target approached from the side. No other effects of target approach direction on estimated TTC were demonstrated. However, recognition distance was significantly lengthened for side vs. head-on target approaches using television monitor ($F=9.49$; $df=1$; $p<.002$) and cinematic ($F=55.69$; $df=1$; $p<.0001$) stimulus presentation methods.

A single significant two-way interaction involving subject age group was found in the stationary observer, actual TTC = 5.0 s data. Age group by target speed significantly influenced estimated TTC, using the video projection methodology in the laboratory ($F=3.03$; $df=4$; $p<.02$); the anomalously high estimated TTC value for the oldest subjects (for side target approaches at low speed) appeared responsible for this effect.

No reliable age group by target approach direction interactions were demonstrated in this data.

Target speed by target approach direction interactions were found for both dependent measures using the television monitor methodology. The effect on estimated TTC was significant at $p<.005$ ($F=7.96$; $df=1$), and the effect on target recognition distance was significant at $p<.008$ ($F=7.11$; $df=1$). Higher target speed, for side target approaches, resulted in higher estimated TTC responses, and **lower** target speed for side target approaches yielded higher recognition distances. Using cinematic stimulus presentation, this interaction effect on recognition distance only was significant at $p<.002$ ($F=9.64$; $df=1$); recognition distance increased with increasing speed for head-on target approaches, but showed little change at different target speeds with target approaches from the side.

No reliable three-way (age group by target speed by target approach direction) interactions were demonstrated in the stationary observer, actual TTC = 5.0 s data.

The next data analyses conducted were for the stationary observer conditions where actual TTC = 7.5 s, beginning with an examination of significant effects of subject age group. Significant main effects of this variable on estimated TTC were demonstrated for all three laboratory methodologies, reflecting exactly the same pattern of results shown for the test conditions where actual TTC = 5.0 s. Effects of age group on estimated TTC were demonstrated using video projection ($F=5.57$; $df=2$; $p<.006$), television monitor ($F=6.0$; $df=2$; $p<.004$), and cinematic ($F=9.95$; $df=2$; $p<.0002$) display techniques. A general trend toward decreasing TTC estimates with increasing age was shown. Also, for cinematic stimulus presentation only, this same effect of age group was indicated on the target recognition distance measure ($F=8.18$; $df=2$; $p<.0007$).

As found at shorter actual TTC levels, the most common main effect demonstrated within these test conditions was for target speed. Estimated TTC increased with increasing target speed using video projection ($F=39.78$; $df=2$; $p<.0001$), television monitor ($F=111.20$; $df=1$; $p<.0001$), and cinematic ($F=143.49$; $df=1$; $p<.0001$) stimulus presentation in the laboratory, as well as in the controlled field trials ($F=30.37$; $df=1$; $p<.0001$). At the same time, target recognition distance **decreased** with increasing target speed using video projection ($F=131.84$; $df=2$; $p<.0001$) and television monitor ($F=307.30$; $df=1$; $p<.0001$) methodologies, while increasing when cinematic display was used ($F=16.53$; $df=1$; $p<.0001$). (No recognition distance data was obtained for the field trials, as explained earlier.)

Main effects of target approach direction for the stationary observer, actual TTC = 7.5 s data were demonstrated for the recognition distance measure, under two laboratory display methodologies. Significantly longer recognition distances were found for target approaches from the side using video projection ($F=8.62$; $df=1$; $p<.004$) and for head-on target approaches using cinematic displays ($F=35.25$; $df=1$; $p<.0001$). No reliable effects of this variable on estimated TTC were demonstrated.

Two-way interactions between age group and target speed resulted in significant effects on estimated TTC using the television monitor ($F=3.26$; $df=2$; $p<.04$) and cinematic ($F=8.16$; $df=2$; $p<.0004$) methodologies in the laboratory, and in the controlled field trials ($F=7.03$; $df=2$; $p<.002$). Proportional increases in estimated TTC with increasing target speed were greatest for the old-old group using the television monitor methodology, but were larger for the young-old group with cinematic stimulus presentation and in the field study. No reliable effects of this interaction on target recognition distance were demonstrated.

The analyses of the stationary observer, actual TTC = 7.5 s data revealed that there were no additional significant interactions among subject age group, target speed, and target approach direction.

Turning to a consideration of the moving observer data, a restricted set of test conditions were included in this project. Accordingly, GLM analyses for the effects of subject age group, target speed, and the interaction of these variables on estimated TTC and target recognition distance were completed, using each of the three laboratory methodologies, for actual TTC = 2.5, 5.0, and 7.5 s. As a reminder, no moving observer conditions were performed in the controlled field trials.

With an actual TTC = 2.5 s, subject age group demonstrated reliable effects--on both estimated TTC and target recognition distance--only using the cinematic display methodology; no significant effects using video projection or television monitor stimulus presentation were observed. For the film-based data, increasing age resulted in significantly briefer estimated TTC responses ($F=5.52$; $df=2$; $p<.006$), and significantly shorter target recognition distances as well ($F=8.10$; $df=2$; $p<.0007$).

Differences in the approach speed of the target when actual TTC = 2.5 s resulted in at least one significant effect with each laboratory methodology. Using video projection, target recognition distance decreased with increasing target speed ($F=9.48$; $df=2$; $p<.0002$), but no effect on estimated TTC was demonstrated. Using the television monitor methodology, increasing target speed resulted in longer estimated TTC responses ($F=17.82$; $df=1$; $p<.0001$), but shorter target recognition distances ($F=45.83$; $df=1$; $p<.0001$). When test stimuli were displayed on 35mm film, estimated TTC increased significantly with increasing target speed ($F=27.84$; $df=1$; $p<.0001$), but target recognition distance was unaffected.

There were no significant interactions of subject age group and target approach speed in the moving observer, 2.5 s actual TTC laboratory data.

When moving observers responded to a test stimulus where actual TTC = 5.0 s, significant main effects of age group were again demonstrated only for the cinematic display methodology. Specifically, increasing subject age resulted in decreasing TTC estimates ($F=6.67$; $df=2$; $p<.002$) and target recognition distances alike ($F=5.80$; $df=2$; $p<.005$).

The effects of target approach speed were more common. When video projection was used to present test stimuli, increasing target speed resulted in shorter target recognition distances ($F=23.26$; $df=2$; $p<.0001$); estimated TTC was not significantly affected, however. Using the television monitor methodology, increasing target speed also resulted in shorter recognition distances ($F=97.58$; $df=1$; $p<.0001$), but, at the same time, estimated TTC grew significantly larger ($F=15.85$; $df=1$; $p<.0002$). With cinematically-presented images, the identical pattern was observed: as target speed increased, subjects recognized the target at shorter distances ($F=21.68$; $df=1$; $p<.0001$) while estimated TTC grew significantly ($F=52.52$; $df=1$; $p<.0001$).

In contrast to the results when actual TTC = 2.5 s, these data demonstrated a significant age group by target speed interaction, though only when test stimuli were projected cinematically. As target speed increased, the drop in recognition distance was proportionately greater for older vs. younger age groups ($F=3.82$; $df=2$; $p<.03$); at the same time, older vs. younger subjects also demonstrated a more pronounced increase in estimated TTC ($F=3.63$; $df=2$; $p<.03$).

Finally, the results for moving observers viewing a test stimulus when actual TTC = 7.5 s indicated the most extensive effects of age group. Increasing subject age resulted in significantly smaller TTC estimates using video projection ($F=6.25$; $df=2$; $p<.003$), television monitor ($F=5.04$; $df=2$; $p<.009$), and cinematic ($F=6.40$; $df=2$; $p<.003$) stimulus presentation methodologies. An effect of age group on target recognition distance was demonstrated only using cinematic display, however ($F=3.60$; $df=2$; $p<.03$), as older subjects demonstrated progressively shorter recognition distances than their younger counterparts for the approaching vehicle target.

Target speed affected the responses of moving observers for an actual TTC = 7.5 s according to the same pattern found for the 2.5-s data. Using video projection to display test stimuli, increasing target approach speed resulted in shorter target recognition distance ($F=33.60$; $df=2$; $p<.0001$), but estimated TTC was not significantly affected. Using television monitor stimulus presentation, increasing target speed resulted in similar reductions in target recognition distance ($F=135.66$; $df=1$; $p<.0001$), but an accompanying increase in estimated TTC was also demonstrated ($F=16.64$; $df=1$; $p<.0001$). When stimuli were presented cinematically, increasing target speed resulted in significantly greater TTC estimates ($F=59.15$; $df=1$; $p<.0001$), but the accompanying increase in target recognition distance failed to reach significance.

No significant interactions between subject age group and target approach speed on either estimated TTC or target recognition distance were found, for any of the laboratory methodologies.

Table 5 summarizes the significant effects of age group, target approach speed, and target approach direction, where applicable, on estimated TTC and target recognition distance in the motion judgment experiments, for each stimulus presentation methodology.

Table 5. Summary of age group (GRP), target speed (TS), and target approach direction (TD) effects on estimated TTC (EST) and recognition distance (DIS) in motion judgment experiments, for all methodologies and actual TTC = 2.5, 5.0, and 7.5 s.

STATIONARY OBSERVER

	2.5 s	VIDEO	2.5 s	TV	2.5 s	FILM
	EST	DIS	EST	DIS	EST	DIS
GRP	N.S.	N.S.	N.S.	N.S.	N.S.	.0003
TS	.0001	.0001	.0139	.0001	N.S.	N.S.
GRP*TS	.0001	N.S.	N.S.	N.S.	N.S.	N.S.
TD	N.S.	N.S.	N.S.	.0001	N.S.	.0001
GRP*TD	.0060	N.S.	N.S.	N.S.	N.S.	N.S.
TS*TD	N.S.	N.S.	.0004	N.S.	N.S.	N.S.
GRP*TS*TD	N.S.	.0376	.0062	N.S.	.0450	N.S.

	5.0 s	VIDEO	5.0 s	TV	5.0 s	FILM	5.0 s	FIELD
	EST	DIS	EST	DIS	EST	DIS	EST	DIS
GRP	.0187	N.S.	.0001	N.S.	.0029	.0006	N.S.	
TS	.0001	.0001	.0001	.0001	.0001	.0001	.0013	
GRP*TS	.0182	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	
TD	.0151	N.S.	N.S.	.0024	N.S.	.0001		
GRP*TD	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.		
TS*TD	N.S.	N.S.	.0053	.0084	N.S.	.0022		
GRP*TS*TD	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.		

	7.5 s	VIDEO	7.5 s	TV	7.5 s	FILM	7.5 s	FIELD
	EST	DIS	EST	DIS	EST	DIS	EST	DIS
GRP	.0057	N.S.	.0040	N.S.	.0002	.0007	N.S.	
TS	.0001	.0001	.0001	.0001	.0001	.0001	.0001	
GRP*TS	N.S.	N.S.	.0406	N.S.	.0004	N.S.	.0022	
TD	N.S.	.0037	N.S.	N.S.	N.S.	.0001		
GRP*TD	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.		
TS*TD	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.		
GRP*TS*TD	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.		

MOVING OBSERVER

	2.5 s	VIDEO	2.5 s	TV	2.5 s	FILM
	EST	DIS	EST	DIS	EST	DIS
GRP	N.S.	N.S.	N.S.	N.S.	.0061	.0007
TS	N.S.	.0002	.0001	.0001	.0001	N.S.
GRP*TS	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.

	5.0 s	VIDEO	5.0 s	TV	5.0 s	FILM
	EST	DIS	EST	DIS	EST	DIS
GRP	N.S.	N.S.	N.S.	N.S.	.0023	.0048
TS	N.S.	.0001	.0002	.0001	.0001	.0001
GRP*TS	N.S.	N.S.	N.S.	N.S.	.0322	.0276

	7.5 s	VIDEO	7.5 s	TV	7.5 s	FILM
	EST	DIS	EST	DIS	EST	DIS
GRP	.0031	N.S.	.0092	N.S.	.0029	.0329
TS	N.S.	.0001	.0001	.0001	.0001	N.S.
GRP*TS	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.

N.S. = not significant

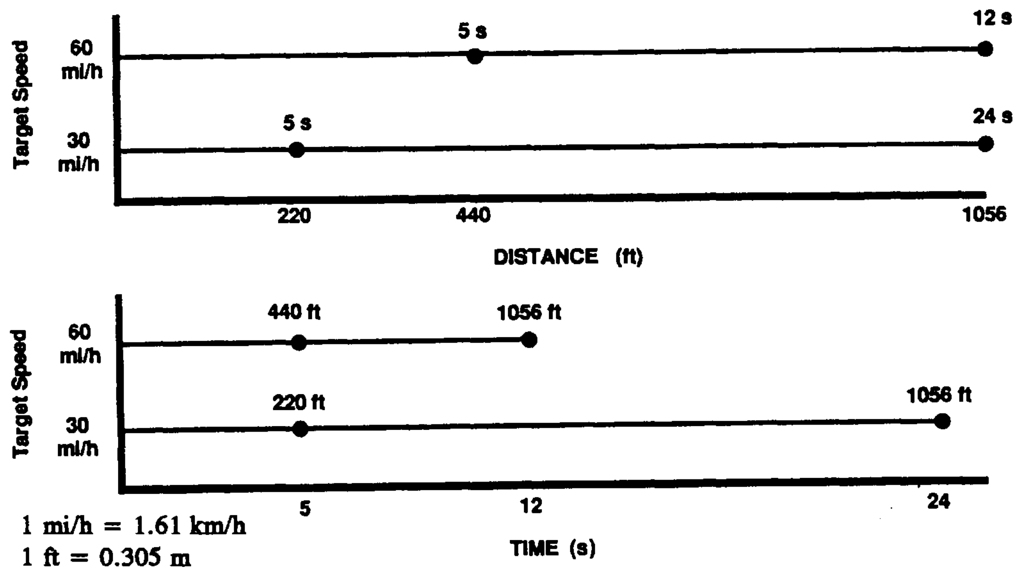
Discussion. The most consistent finding in the motion judgment experiments, across all test conditions, was underestimation of time-to-collision. This trend held true for subjects of all age groups and at all target approach speeds, though in the laboratory the magnitude of underestimation of TTC was frequently greatest for the oldest subjects (75+ years of age), at the lowest target speed of 30 mi/h (48 km/h).

Subjects also evidenced consistent underestimation of TTC in the few field trials performed, but differences due to age group were selectively diminished. At a shorter actual TTC (5.0 s), all age groups' responses increased modestly with increasing target speed, but did not differ significantly from each other. At the longer actual TTC (7.5 s), older subjects' TTC estimates grew more dramatically with increasing target approach speed, while the estimates of the young/middle-age group remained almost unchanged. This latter finding was documented in a significant age group by target speed interaction.

To an extent, the exaggerated underestimation of TTC by older subjects may be related to the significantly shorter target recognition distances often evidenced by these study participants. With less time to track the oncoming vehicle, after having resolved it as the target stimulus on a given trial, less processing of angular expansion information would be permitted. Assuming such cues to be critical for accurate motion perception, a trend toward larger perceptual errors for individuals with less reliable information upon which to base their judgments is not surprising.

Another prominent pattern in these data, as noted above, was the increasing underestimation of TTC with decreasing target speed. To better understand this phenomenon, the reader should refer to the distance and time diagrams in figure 34.

A target vehicle starting 1,056 ft (322 m) from the observer, traveling at 30 mi/h (48 km/h) or 44 ft/s (13 m/s), would require 24 s to reach the observer's position. At a 5-s actual TTC, its approach was observed for 19 s, during which time it had traveled a distance of 836 ft (255 m). When the stimulus was removed from view in this experiment, it was still approximately 220 ft (67 m) away from the observer. The same target vehicle traveling 60 mi/h (96 km/h) or 88 ft/s (27 m/s) and starting from the same location, however, would require only 12 s to reach the observer's position. At the 5-s actual TTC, its approach was observed for only 7 s, during which time it had traveled 616 ft (188 m); when this stimulus was removed from view, it was still approximately 440 ft (134 m) away. Thus, **at the lower target approach speed, the oncoming vehicle's angular size when removed from view was twice as large as when it was approaching twice as fast.** A quicker response (connoting greater underestimation of TTC) under these circumstances for older drivers--who have been hypothesized to rely principally or exclusively on size cues--is therefore less surprising.



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

Figure 34. The interrelationship between time and distance traveled for a target vehicle starting from a common position and approaching at different speeds.

Next, there is one aspect of the pattern(s) of differences in estimated TTC between age groups deserving closer scrutiny. In particular, two distinct patterns of response were observed where only one was expected. Since the literature describing age-related functional decline indicates a monotonic trend in diminished sensory, perceptual, cognitive, and psychomotor capacity with advancing age, the accuracy of subjects' perceptual judgments might be expected to vary accordingly in this research. Indeed, in looking at the 5.0- and 7.5-s TTC data, over 70 percent of the valid trials for the oldest group of subjects (75+ years of age) conformed to the pattern labeled "A" in figure 35 below, with respect to estimated TTC. But, when actual TTC = 2.5 s, nearly 60 percent of valid trials for the oldest subjects conformed to pattern "B"--instead of the expected monotonic shift in the magnitude of this response with advancing age, an apparent reversal in the behavior of old-old subjects was noted. Their responses shifted back toward those of the 18-55 age group, contrary to the trend shown by the young-old (56-74 age group) subjects.

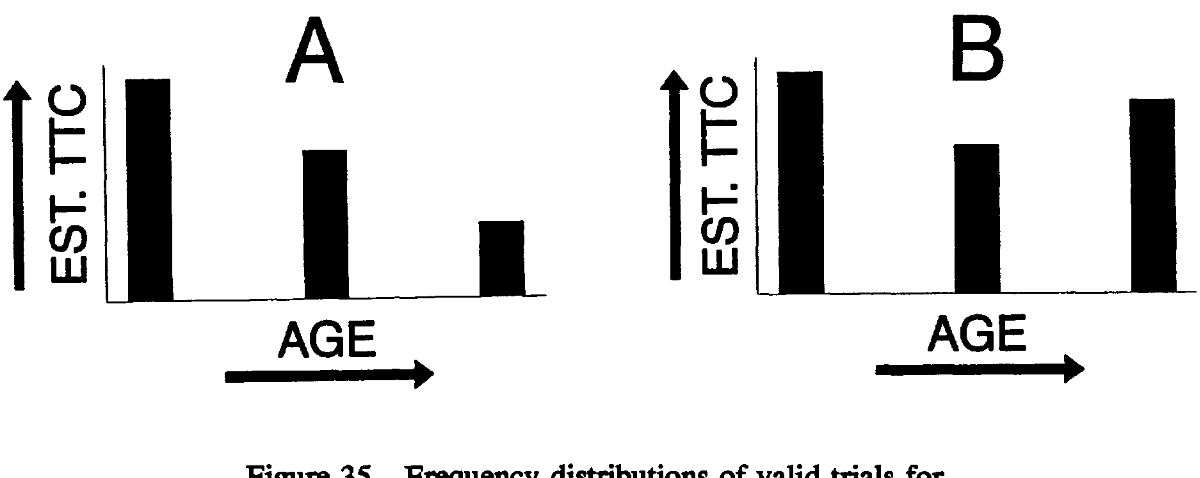


Figure 35. Frequency distributions of valid trials for 75+ age group in motion judgment experiments.

An explanation for this inconsistency in the data lies in the distribution of valid responses in this test condition. It was often noted by the experimenter that subjects performed a TTC response virtually as soon as the stimulus was removed from view, and that older subjects did this more often than younger subjects. Thus, estimated TTC was, on average, always less than the actual TTC under all test conditions. When actual TTC = 2.5 s, however, the target vehicle was at its closest (simulated) approach to the observer, and this abbreviated response behavior was most common. If a subject's response latency was so fast on a given trial that upon subtracting his/her simple reaction time, a value less than zero was indicated, that trial was declared invalid and excluded from these analyses.

In examining the responses of the subjects ages 75 years and older in the 2.5-s TTC conditions, a group mean of 1.12 s for **all valid responses** was calculated. Dividing the old-old group into two equal subsamples according to frequency of valid TTC estimates, those in the bottom half--i.e., those with the greatest number of abbreviated responses that were invalidated when the simple RT correction was applied--showed a mean of .81 s for the responses which **did** make it into the analyses. At the same time, the top half of the old-old sample (based on frequency of valid responses) showed a mean estimated TTC of 1.3 s. Clearly, the poorest performers among the 75+ years of age group, defined as those who perceptually misjudged (underestimated) TTC by the largest amount, were the same individuals most likely to drop out of the analyses, as described above.

It may thus be concluded that the age effect described in pattern "B" above was anomalous, reflecting a selection bias in which data for old-old subjects most like their younger counterparts was more likely to be analyzed than that for the more divergent members of this 75+ age group. This conclusion reinforces the monotonic nature of changes in drivers' motion perception capabilities with advancing age, and suggests that the findings in this study for the 5.0- and 7.5-s TTC conditions are most appropriate and useful for the development of potential countermeasures in this research.

GAP ACCEPTANCE EXPERIMENTS

Age-related differences in drivers' safe-vs.-unsafe gap judgments were measured in laboratory and controlled field experiments for the following specific traffic maneuvers: (1) left turns against traffic, (2) a two-lane highway crossing, (3) right turns in front of traffic at an intersection, (4) freeway merging, (5) freeway weaving and exiting, (6) car following, (7) overtaking, and (8) passing on a two-lane highway. The laboratory and field study methodologies are described first, followed by a combined results and discussion section.

LABORATORY DATA COLLECTION USING DRIVING SIMULATOR

Objectives. The primary gap acceptance study objective was to measure age-related differences in "safe-to-proceed" vs. "unsafe-to-proceed" decisions to initiate designated vehicle maneuvers in a range of familiar (simulated) traffic situations, based upon the perceived speed and distance of approaching conflict vehicles. It deserves emphasis that "safe (vs. unsafe) to proceed" refers to a subjective judgment by the drivers in this study, and that **relative** differences in such judgments are presently at issue--as opposed to the absolute magnitudes of gap judgments. Additionally, the evaluation of presentation format (large-screen video vs. cinematic vs. television monitor) for collecting the driver performance measures of interest defined a second objective of this study.

Experimental Variables. The gap acceptance laboratory study included two independent variables and one blocking variable. The independent variables were conflict vehicle approach speed and driver age (group). The blocking variable was maneuver type. It may be noted that observer vehicle speed did **not** vary within a given block of test trials in this study; i.e., for any given driving maneuver, only a single observer vehicle speed was examined. Also, the independent variables were not completely crossed--for some maneuver types, multiple conflict vehicle approach speeds were examined, while for others only a single conflict vehicle speed was examined.

The dependent variables on all gap acceptance test trials were the recognition distance for an approaching (conflict) vehicle as the target stimulus, and each subject's judgment of the instant during that conflict vehicle's approach that a given maneuver could no longer be safely initiated. That is, at the beginning of each test trial, the approaching (conflict) vehicle was always sufficiently far removed from the observer that the maneuver was unequivocally judged to be safe to proceed. Then, at some point the proximity and/or perceived speed of the approaching vehicle resulted in a judgment that it was no longer safe to proceed with the maneuver in question. Pinpointing the (apparent) separation of the conflict vehicle from the observer at the time this judgment was made, as well as the initial target recognition distance, were the specific measurement objectives.

Eight levels of the blocking variables--maneuver types--were examined using the large-screen video methodology. Maneuvers were distinguished by the following operational characteristics and by the intentions of the test subject on each trial:

1. Left turn against traffic at an intersection, turning from a 45+ mi/h (72+ km/h) highway onto a stop sign-controlled secondary (residential) road.

2. Crossing a two-lane highway in front of through traffic, approaching from the driver's side, from a stationary position at a stop sign on an intersecting road.

3. Turning right in front of through traffic approaching from the driver's side on a 45+ mi/h (72+ km/h) highway, from a stationary position at a stop sign on an intersecting (secondary) road.

4. Entering a freeway on an acceleration ramp and merging with traffic on the mainline, from the frame of reference of a stationary observer near the ramp gore point.

5. Executing a lane weave to the right to exit a freeway, in conflict with a vehicle entering the freeway from a ramp.

6. Car following on a two-lane highway, at an observer vehicle speed of 45 mi/h (72 km/h).

7. Overtaking a lead vehicle at a speed of 55 mi/h (88 km/h) on a two-lane highway.

8. Initiating a maneuver to pass a lead vehicle on a two-lane highway against oncoming traffic, from a speed of 45 mi/h (72 km/h).

For data collection using cinematic and television monitor display systems, the freeway exit/weave maneuver (maneuver 5 in the paragraph above) was omitted because of the inability to simultaneously present a dynamic view on two projection screens (the front and right side screens) for the cinematic display.

The speed of the conflict vehicle varied across different numbers of levels, depending upon maneuver type. For the left turn, crossing highway, and turning-right-onto-highway maneuvers using the large-screen methodology, four different conflict vehicle approach speeds were examined: 20, 30, 45, and 60 mi/h (32, 48, 72, and 96 km/h). The cinematic and television monitor methodologies examined only two conflict vehicle approach speeds: 30 mi/h (48 km/h) and 60 mi/h (96 km/h). For the entering freeway maneuver (with all display methodologies) and the freeway exit/weaving maneuver (large-screen video methodology only), the conflict vehicle speeds were 60 mi/h (96 km/h) and 30 mi/h (48 km/h), respectively. In each of the two-lane highway maneuvers tested--car following, overtaking a lead vehicle (without oncoming traffic), and passing a lead vehicle (with oncoming traffic)--the lead vehicle in all methodologies traveled at 45 mi/h (72 km/h). In the car following trials the lead vehicle accelerated from the 45 mi/h (72 km/h) speed to gradually widen the gap between vehicles. In the passing maneuver trials, the oncoming (conflict) vehicle speed was 45 mi/h (72 km/h), the same as the observer and lead vehicles in this situation.

As in the motion judgment data collection, the driver age group varied across three levels: 18-55, 56-74, and 75+ years of age. The test subjects who participated in the gap acceptance studies were, in fact, drawn from the motion judgment studies test sample.

Test Conditions. In figure 36, a test conditions matrix is shown for the gap acceptance trials using the large-screen video methodology. Figure 37 shows the test conditions completed using the cinematic and television monitor methodologies. The numbers of test conditions each subject participated in were 17, 10, and 10, for the large-screen video, cinematic, and television monitor presentation formats, respectively.

Test Apparatus. The large-screen simulator and the television monitor display systems described in the motion judgment laboratory experiments were also employed for data collection in the gap acceptance experiments. The identical subsidiary tracking task was again used for moving observer trials.

Maneuver Type (all images filmed)

		Left turn against traffic	(Acceptance of gap) crossing highway	(Acceptance of gap) turning right onto highway	Enter freeway	Lane weaves on freeway	Car following on two-lane highway (1)	Overtaking lead vehicle on two-lane highway	Passing on two-lane highway (2)
Observer vehicle speed (mi/h)		0	0	0	0	55	45	55	45
Conflict vehicle speed (mi/h)	60	X	X	X	X		X		
	45	X	X	X			↑	X	X, X
	30	X	X	X		X			
	20	X	X	X					

1 mi/h = 1.61 km/h

(1) The lead vehicle initially traveled at the same speed (45 mi/h) as the observer vehicle for this maneuver, then constantly accelerated to widen the separation distance.

(2) Conflict vehicle speeds indicated in matrix pertain to lead vehicle and oncoming vehicle, both traveling at 45 mi/h.

Figure 36. Gap acceptance laboratory study test conditions: large-screen video methodology.

Maneuver Type (all images filmed)

		Left turn against traffic (1)	(Acceptance of gap) crossing highway (1)	(Acceptance of gap) turning right onto highway (1)	Enter freeway (1)	Car following on two-lane highway (2)	Overtaking lead vehicle on two-lane highway	Passing on two-lane highway (3)
Observer vehicle speed (mi/h)		0	0	0	0	45	55	45
Conflict vehicle speed (mi/h)	60	b	d	d	c	a		
	45					↑	a	a
	30	a	c	c				

Letters a, b, c, and d identify blocks of trials, as described on facing page of text.

1 mi/h = 1.61 km/h

(1) Lead-in footage showing driver's approach to a decision point was not presented to subjects; all responses made from static position at point of maneuver.

(2) The lead vehicle initially traveled at the same speed (45 mi/h) as the observer vehicle for this maneuver, then constantly accelerated to widen the separation distance.

(3) Conflict vehicle speeds indicated in matrix pertain to lead vehicle and oncoming vehicle, both traveling at 45 mi/h.

Figure 37. Gap acceptance laboratory study test conditions: cinematic and television monitor methodologies.

Test Stimuli. Test stimuli were filmed at three different locations. A cloverleaf in Doylestown, PA (PA Routes 611 and 202) served as the filming site for the freeway entrance and the freeway exit/weave maneuvers. This cloverleaf was chosen because an unopened highway segment (not used for filming) allowed for fewer interruptions and limited traffic control requirements during filming activities. The highway crossing maneuver was filmed on a two-lane highway in Doylestown, PA (PA Route 313) where a straight level expanse of roadway provided sufficient sight distance to the conflict vehicle, that the maneuver would be considered safe to initiate (in the driving simulator) when the conflict vehicle was presented at its highest speed. The remaining maneuvers (right turn in front of traffic, left turn across traffic, car following, car overtaking, and car passing) were filmed on NJ Route 29, south of Frenchtown. This site provided a high-speed two-lane highway with few intersecting routes. Traffic at each filming site was stopped only during the actual filming of each maneuver, and police backup was provided by township police at each location.

The actual filming of the test stimuli was conducted as described for the motion judgment experiments, with a filming vehicle serving as the platform for three cameras. Both the filming and the target (conflict) vehicles were instrumented as previously described.

Data Collection Protocol. Data collection for the gap acceptance trials using the large-screen video methodology proceeded after a break, following the motion judgment trials, in each subject's first visit to the laboratory. A different presentation order was used for each subject within an age group to counterbalance the possible effects of fatigue and boredom, using the random access capability of the videodisc playback system as described for the motion judgment data collection.

The "last safe moment to proceed" maneuver judgment was obtained using the same brake pedal depression response, and the steering wheel-mounted response button was again used to obtain the target vehicle recognition distance dependent measure, as described earlier for the motion judgment studies. Subjects also used the steering wheel to perform the subsidiary tracking task on the head's-up cathode ray tube (CRT) monitor for moving observer test trials. Performance requirements for the subsidiary tracking task were set at a low level of difficulty, since the range of observer motion shown on the various test trials rarely deviated from straight ahead.

As in the motion judgment data collection, the PC had access to files on each scene to be played. These files contained the observer vehicle/conflict vehicle separation distance for each frame of all scenes for the gap acceptance trials.

At the beginning of each trial, the experimenter paused the first frame of the scene on the screen that would present the conflict vehicle's approach, and described the scenario about to occur for the trial type. This gave the subject a proper frame of reference in which the gap acceptance judgment should be made. For example, the script for the passing maneuver trial was as follows:

> You will be using the tracking device while you watch this scene. For this scene, you will be following the gold car you see presented on the screen in front of you. You will be straddling the center line, because you wish to pass the gold car. At some point during this scene, a white car will approach you from a distance in the oncoming lane.
>
> You will make two responses for this scene. First, press the button on the steering wheel at the earliest moment when you can identify that the distant object in the opposing lane is a car. Then, press the brake at the **last possible safe moment** to pass the gold car.

Data collection for the gap acceptance trials using the cinematic and television monitor methodologies also followed motion judgment data collection during each subject's second visit to the laboratory. As described in the motion judgment studies, randomized trial orders were not permitted during data collection with the 35mm cinematic methodology. Again, only one order of presentation of stimuli for trials using "as filmed" conflict vehicle speed trials was permitted, as well as one order of presentation for trials where the conflict vehicle was shown approaching at an increased speed. Laboratory data collection was therefore divided into four blocks: (a) front windshield target approaches at "as filmed" speed; (b) front windshield target "increased speed" approaches; (c) left side target approaches at "as filmed" speed; and (d) left side target "increased speed" approaches. The specific trials included in each block (a)-(d) are indicated in figure 37.

Four different block order presentations were incorporated into the 35mm cinematic data collection protocol, such that six subjects in each of the three age groups tested received the same order of presentation. Several trials presented using the television format were eliminated from the cinematic presentation that were conducted using the television presentation format. The remaining cinematic trials were counterbalanced according to different orders of presentation from subject to subject, and were shown in the same sequence for the television presentation as previously described in the motion judgment study.

Again, the experimenter described the scenario for which the gap acceptance judgment would be made, prior to the trial onset. The same scripts used in the large-screen video data collection protocol were used for the cinematic and television monitor presentation formats.

CONTROLLED FIELD STUDY

Objectives. The objective of this field study was to empirically validate the measurements of subjects' gap acceptance judgments obtained in the laboratory, for a limited set of test conditions, using the same stimuli presented to the same drivers in the same settings as filmed. As in the lab study, **relative** differences in gap judgments are at issue in the research design for field data collection. However, a post-hoc analysis based on stopping sight distance calculations was also performed to gauge the level of safety of subjects' gap judgments in absolute terms, as reported in the discussion section to follow.

Experimental Variables. In the gap acceptance field study, the independent variables were limited to: (1) the speed of approach of the conflict vehicle, and (2) the age (group) of the driver/test subject. Maneuver type served as a blocking variable, with two different maneuvers examined in this study--left turns against traffic at intersections, and gap acceptance for a right turn at an intersection ahead of oncoming traffic. The dependent variable for all trials was the gap associated with each driver's judgment of the instant during the conflict vehicle's approach that the maneuver in question could no longer be safely initiated. As in the laboratory study, the approaching (conflict) vehicle was always sufficiently far removed from the subject that the maneuver was unequivocally judged to be "safe to proceed" at the beginning of each test trial.

Two levels of conflict vehicle approach speed were examined: 30 mi/h (48 km/h) and 60 mi/h (96 km/h). Given the maneuver types of present interest, all responses were made by stationary observers; for the left turn maneuver, the driver was positioned in the right lane of a two-lane highway waiting at an intersection to turn against traffic onto a secondary/residential road, and for the right turn maneuver the driver was positioned at a stop sign on the left shoulder of a secondary/residential road while observing a vehicle approaching from the left (i.e., intersecting at 90°) on the highway. The shoulder position for the right turn maneuver was chosen so as not to impede following traffic, as well as to eliminate obstructing the view of the conflict vehicle by traffic turning left from the secondary road.

The levels of the variable driver ages (group) were 18-55, 56-74, and 75+ years of age, with the same drivers participating in the gap acceptance field study as in the gap acceptance laboratory studies.

Test Conditions. Figure 38 shows the test conditions completed for the gap acceptance field study. Each subject thus completed four trials.

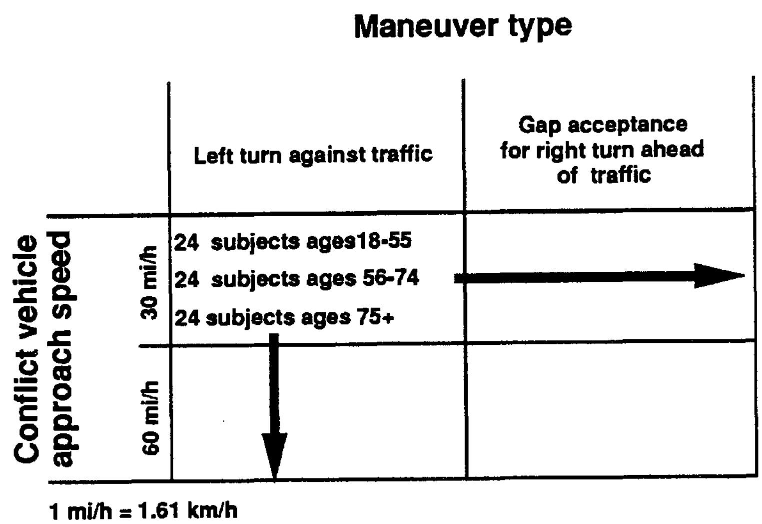


Figure 38. Gap acceptance field study test conditions.

Test Apparatus. The primary vehicle instrumentation needs included hardware/software systems to monitor the distance traveled by the conflict vehicle from a known reference point on each trial and to record the subjects responses for "unsafe to proceed" gap judgments. In this study, where each subject made a "last safe moment to proceed" judgment, an accurate log of target vehicle movement was essential. With this information, calculation of separation distance at the instant a subject responded was performed after the trial was completed. A hand-held response button was used by the subject to signal the instant the initiation of the intended maneuver became unsafe.

Conflict vehicle travel distance was monitored by a distance measuring unit (DMU) located in the conflict vehicle. The conflict vehicle was positioned approximately 1 mi (1.61 km) from the test vehicle, and was hidden from sight at the onset of each trial. Once the conflict vehicle began its approach, the DMU recorded distance (ft) traveled from a predetermined location marked on the shoulder of the roadway. The subject vehicle was equipped with a transmitter that immediately notified the DMU in the conflict vehicle when the response button was pushed by the subject for his/her "last safe moment" judgment. When the test subject pushed the response button, the DMU display froze. The confederate driver radioed the distance traveled to the experimenter via two-way radio; the experimenter then entered the distance into the data collection computer in the test vehicle.

Test Stimuli. The same white, Mercury Marquis sedan used during filming of test scenes for the laboratory experiments served as the target stimulus (conflict vehicle) in the controlled field study. It was driven by a confederate, who was in radio contact with the experimenter in the subject vehicle. When the subject vehicle was in place, the experimenter radioed the confederate that the approach could begin. The confederate then waited for a long break in the traffic stream to begin the approach toward the subject vehicle. Once the test vehicle was in sight, the confederate flashed the headlights on the conflict vehicle as a signal to the subject that this was the vehicle about which the safe/unsafe gap acceptance judgment should be made.

Data Collection Protocol. Field data collection for the gap acceptance study followed data collection for the motion judgment field study conducted on NJ Route 29. Data collection for both field studies was collected in a single session, with the same groups of subjects who were transported to the test site to perform the TTC judgments.

For trials involving safe/unsafe judgments about left turns against oncoming traffic, the subject sat in the passenger seat. This allowed the experimenter to watch for other traffic during a test trial and to move the vehicle out of the way of any following traffic and to move the vehicle off the roadway once a subject had responded. Trials that were interfered with were repeated at the end of the test sequence. This protocol allowed a subject to focus attention solely on the conflict vehicle, and eliminated any competing driving tasks from distracting from the maneuver gap judgment. On right turn trials, where a conflict vehicle approached at 90° from the left (driver's) side, the subject sat in the driver's position to make his/her response, after the experimenter had positioned the vehicle as required at the intersection.

Field data collection was blocked according to maneuver type. All right turn gap acceptance judgments were obtained before proceeding with the left turn trials. Within each of these blocks, the speed of the conflict vehicle was counterbalanced across subjects to control for order effects: equal numbers of subjects in each age group observed the conflict vehicle approaching at speeds of 30 mi/h (48 km/h), then 60 mi/h (96 km/h) vs. 60 mi/h (96 km/h), then 30 mi/h (48 km/h).

RESULTS AND DISCUSSION

Results. The organization of material in this section parallels that presented earlier for the motion judgment experiments: bar graphs summarizing mean responses of each group for each dependent measure using the various stimulus presentation methodologies, with corresponding tables of descriptive statistics presented in appendix D. These data will be reported on a maneuver specific basis. The order of maneuvers for which results are presented is: left turn, highway (two-lane) crossing, right turn, freeway merging, car following, car overtaking, passing (on two-lane highway), and freeway exit/weave.

Accompanying text introduces the content of all figures and tables and reports on tests of observed differences for statistical significance. Main effects and interactions of the included independent variables (age group and target speed), within blocks of test conditions defined by maneuver type and stimulus presentation methodology, were analyzed with General Linear Models Procedure (PROC GLM) in SAS as reported earlier, using the same assumptions and program analysis options for repeated-measures designs.

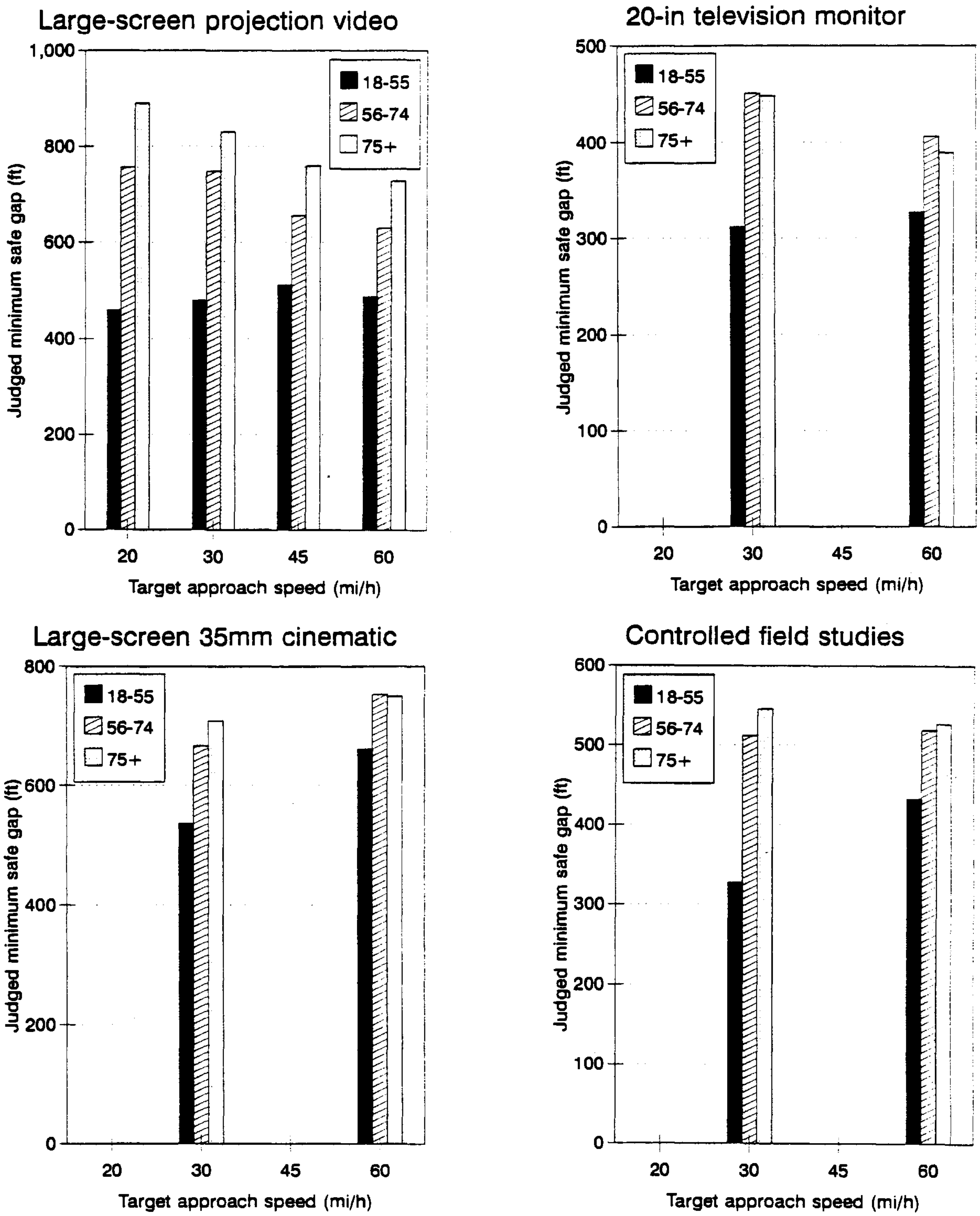
The results for target recognition distance and the judged minimum safe gap to proceed with a left turn maneuver from a stationary position at an intersection are presented in figures 39 and 40, and in tables 23 through 26 for the three subject age groups with varying approach speeds of the oncoming vehicle target. Figures 41 and 42, and tables 27 through 29 present the results for stationary observers judging the minimum safe gap to cross a two-lane highway, with corresponding target recognition distances. The results for a right turn at an intersection into traffic on a two-lane highway ahead of an oncoming vehicle are shown in figures 43 and 44 and tables 30 through 33.

In figures 45 and 46, and tables 34 through 36, results for target recognition distance and the judged minimum safe gap to proceed with a freeway merge maneuver from a stationary position at the gore of the entry ramp are presented for subjects in each of the three age groups included in the study. In figure 47 and tables 37 through 39, judged minimum safe gap distances only are presented for the car following maneuver; no target recognition distance measures were obtained under this condition. Similarly, figure 48 and tables 40 through 42 present the judged minimum safe gap distances to perform the car overtaking maneuver, as no target recognition distance measures were obtained for this condition. Figures 49 and 50, and tables 43 through 45 present the results for target (oncoming vehicle) recognition distance and judged minimum safe gap to perform a (single vehicle) passing maneuver on a two-lane highway. Only one target vehicle approach speed--which varies according to maneuver--is reflected in the results summarized in figures 45 through 50 and tables 34 through 45.

Results for the freeway exit/weave maneuver, for which gap judgment responses were obtained only, using the large-screen video projection methodology in the laboratory, are presented exclusively in table 46 in appendix D. Since only a single data collection methodology was employed, no figure was prepared to summarize the results for this maneuver.

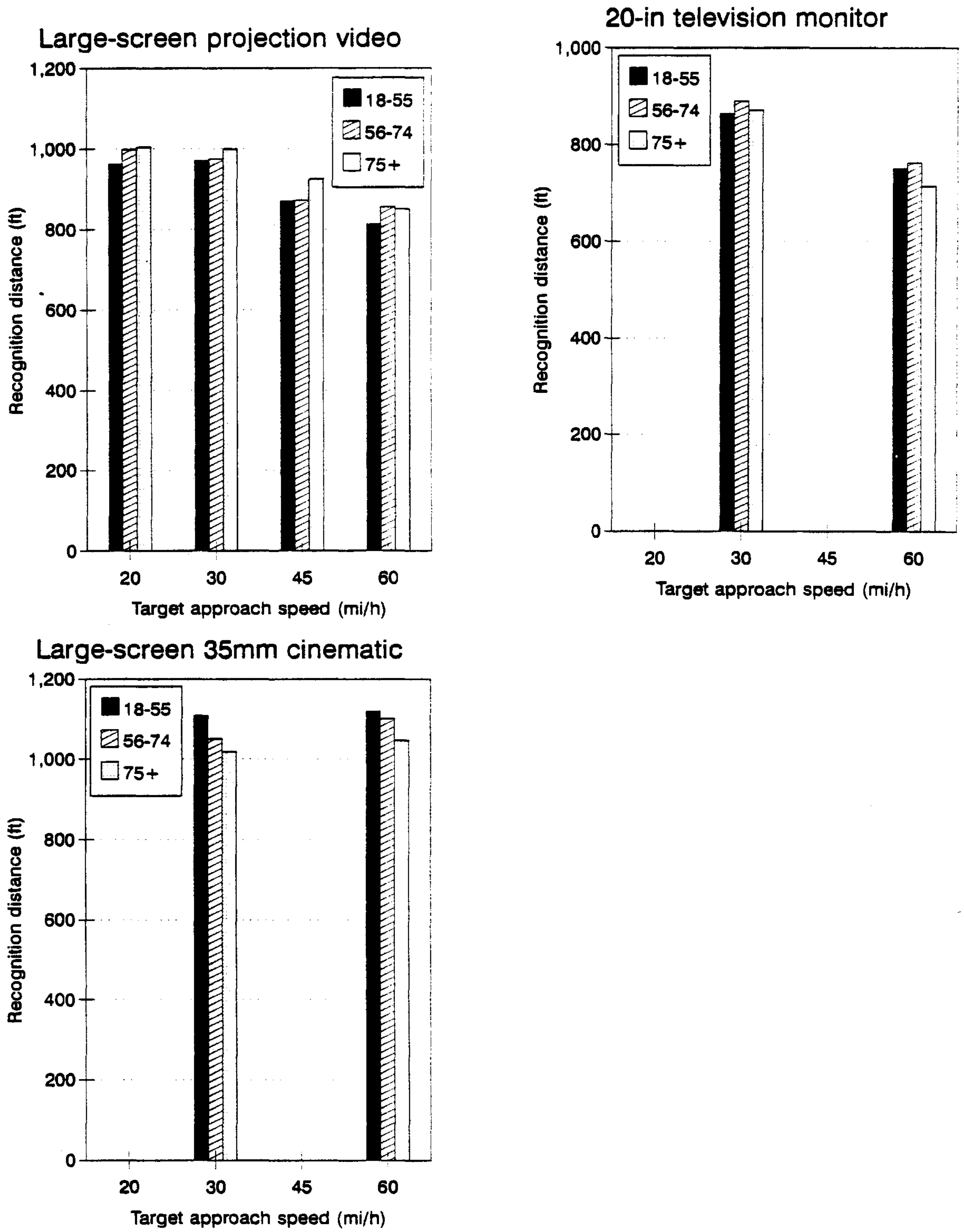
As in the motion judgment experiments, the F-tables produced by SAS for the present data analyses have been deferred to appendix E. The outcomes of these tests for significant differences in the gap acceptance results are summarized as follows, on a maneuver-by-maneuver basis.

A significant effect of age group on the judged minimum safe gap to perform the left turn maneuver was demonstrated using all laboratory test methodologies, such that increasing subject age resulted in larger gap requirements. The same trend was observed in the controlled field data, but failed to reach significance. The magnitude of the age group effects was given by $F=20.66$ ($df=2$; $p<.0001$) using the video projection methodology, by $F=4.48$ ($df=2$; $p<.01$) using the television monitor methodology, and by $F=3.21$ ($df=2$; $p<.05$) when the target stimulus was presented cinematically. In addition, effects of age group on target recognition distance were demonstrated using the 35mm film stimulus display methodology, as younger subjects recognized the target vehicle at significantly greater distances than older subjects ($F=6.04$; $df=2$; $p<.004$). No reliable effect of age group on this dependent measure was found for the video projection or television monitor methodologies, and target recognition distance was not measured in the controlled field trials.



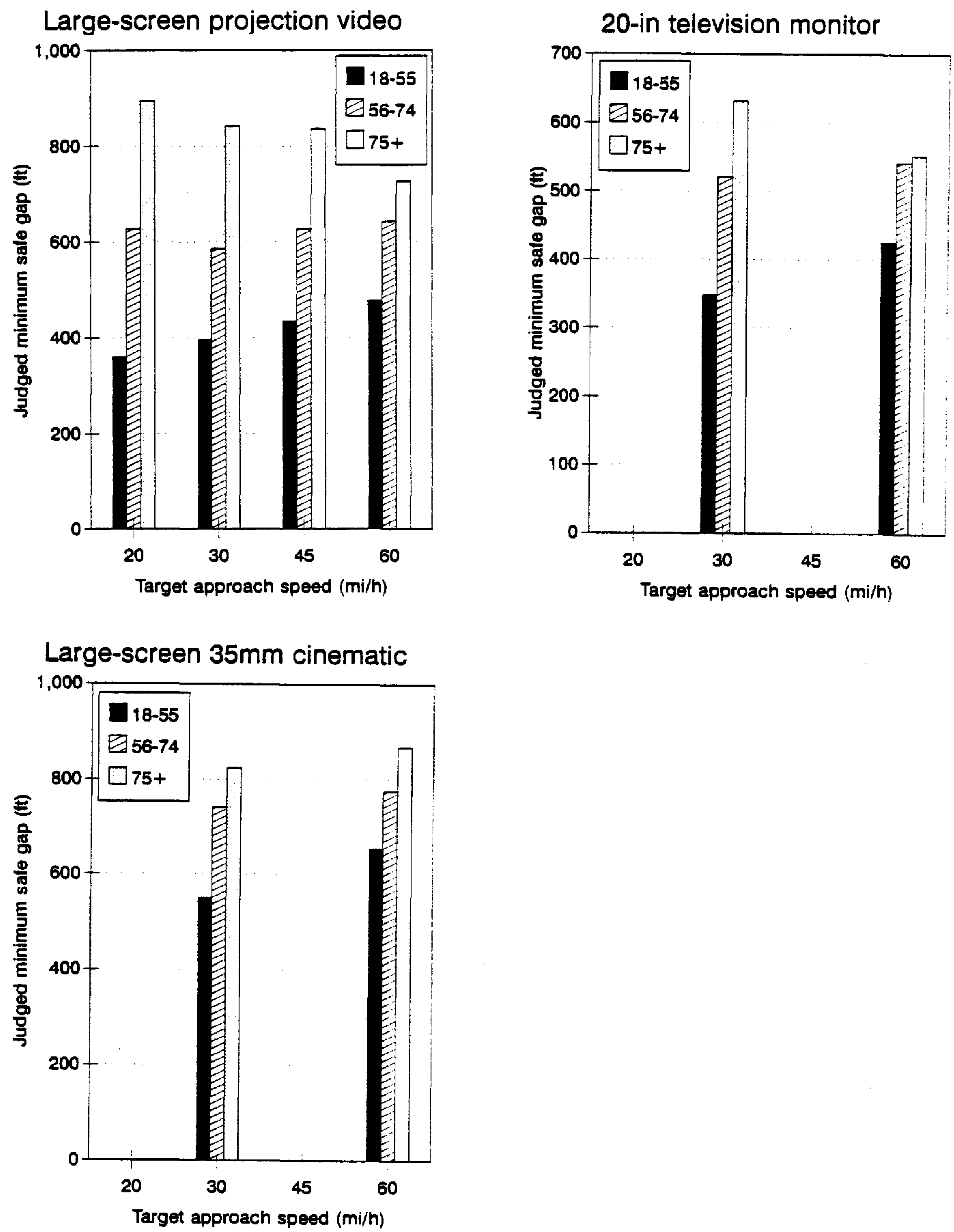
1 mi/h = 1.61 km/h
1 ft = 0.305 m

Figure 39. Judged minimum safe gap (ft) for stationary observers in three age groups to perform a left turn against traffic maneuver.



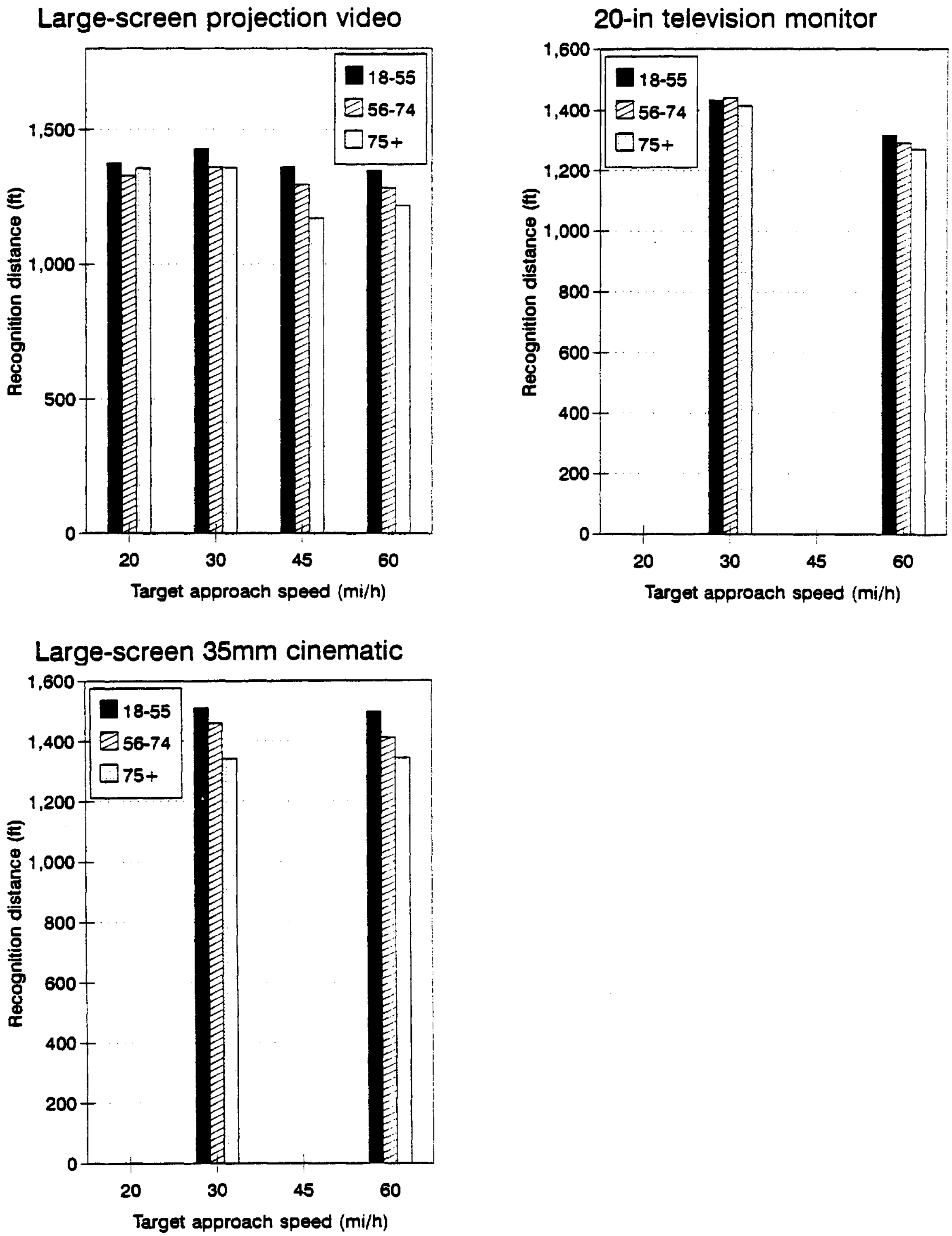
1 mi/h = 1.61 km/h
1 ft = 0.305 m

Figure 40. Target recognition distance (ft) for stationary observers in three age groups to perform a left turn against traffic maneuver.



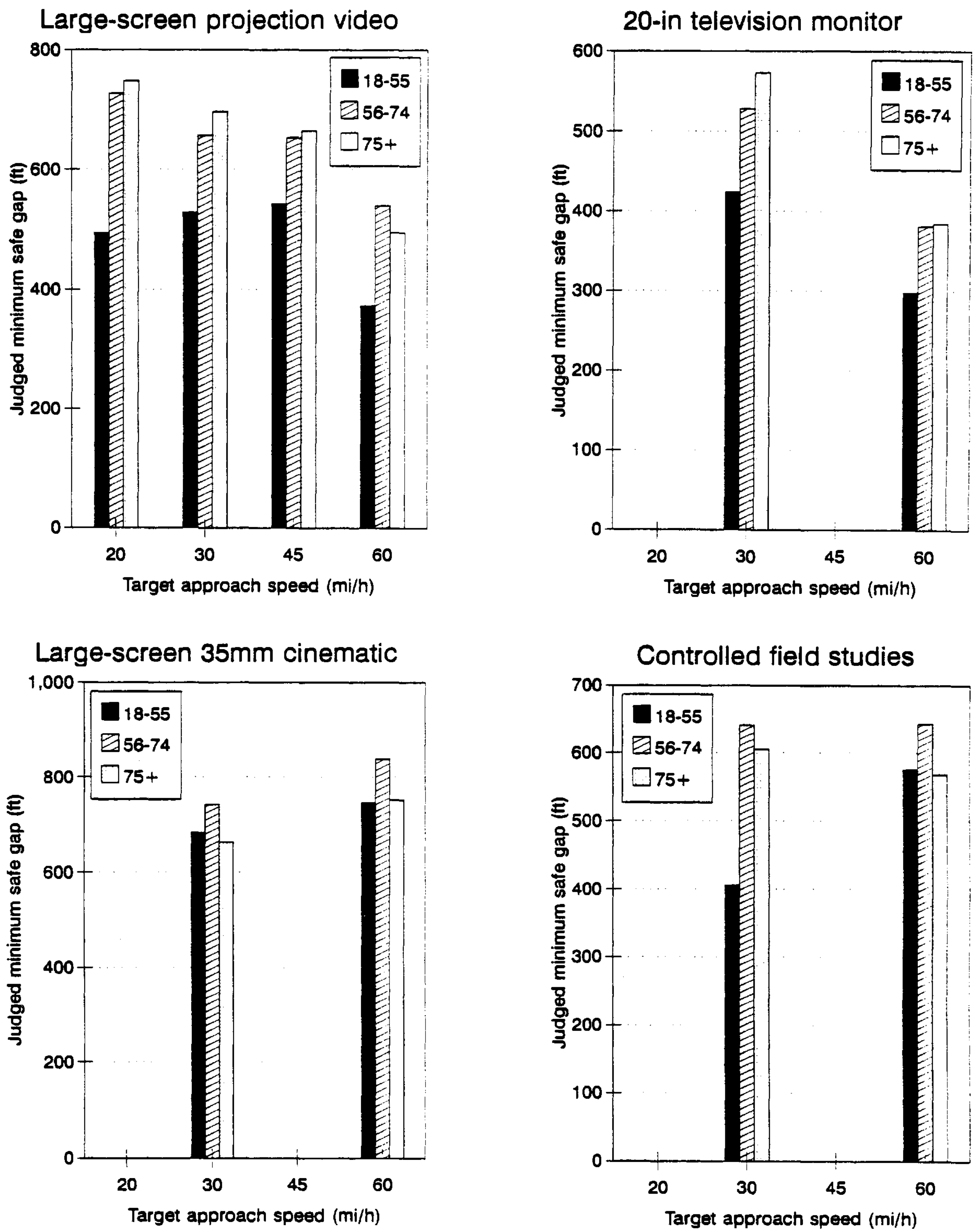
1 mi/h = 1.61 km/h
1 ft = 0.305 m

Figure 41. Judged minimum safe gap (ft) for stationary observers in three age groups to perform a two-lane highway crossing maneuver.



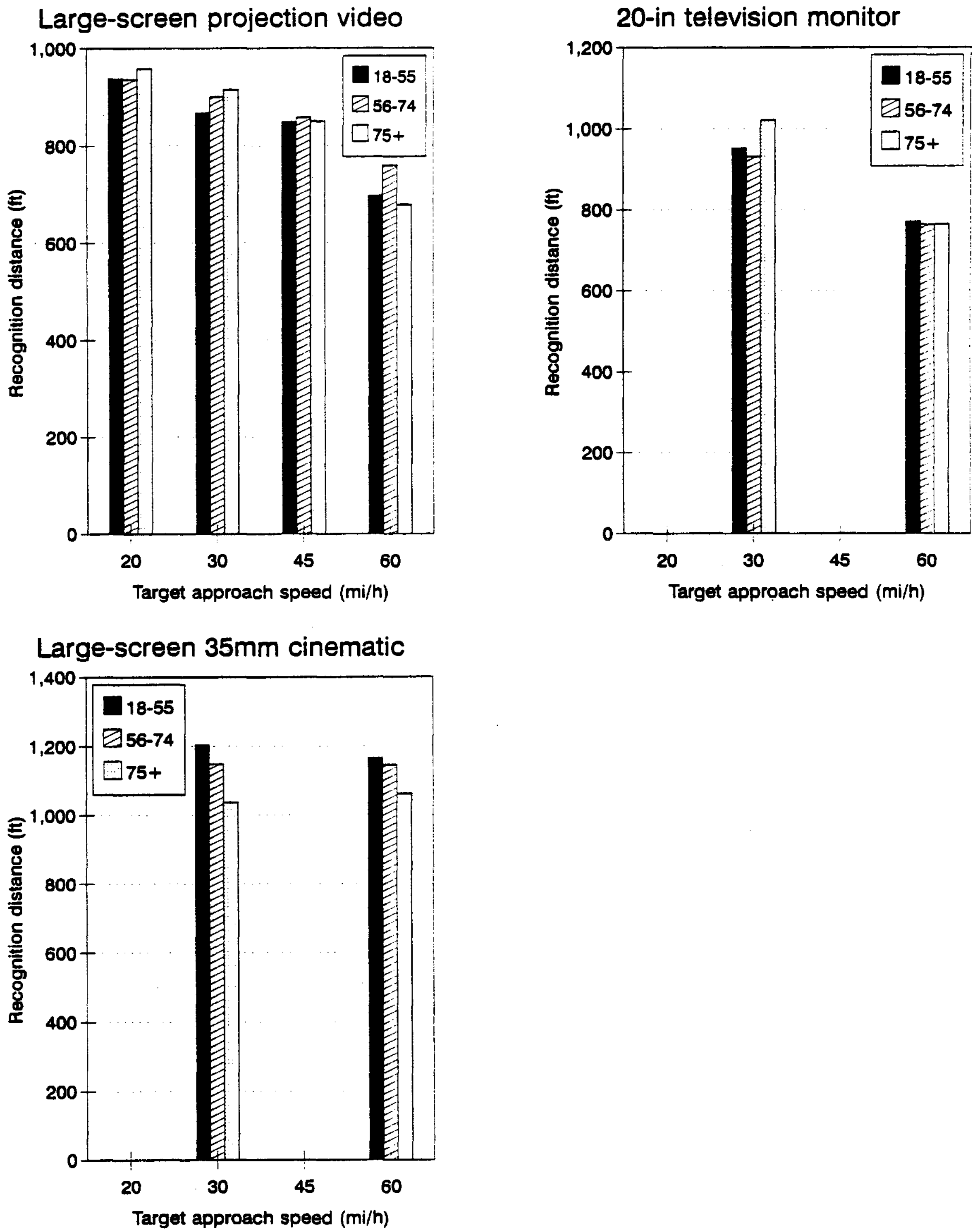
1 mi/h = 1.61 km/h
1 ft = 0.305 m

Figure 42. Target recognition distance (ft) for stationary observers in three age groups to perform a two-lane highway crossing maneuver.



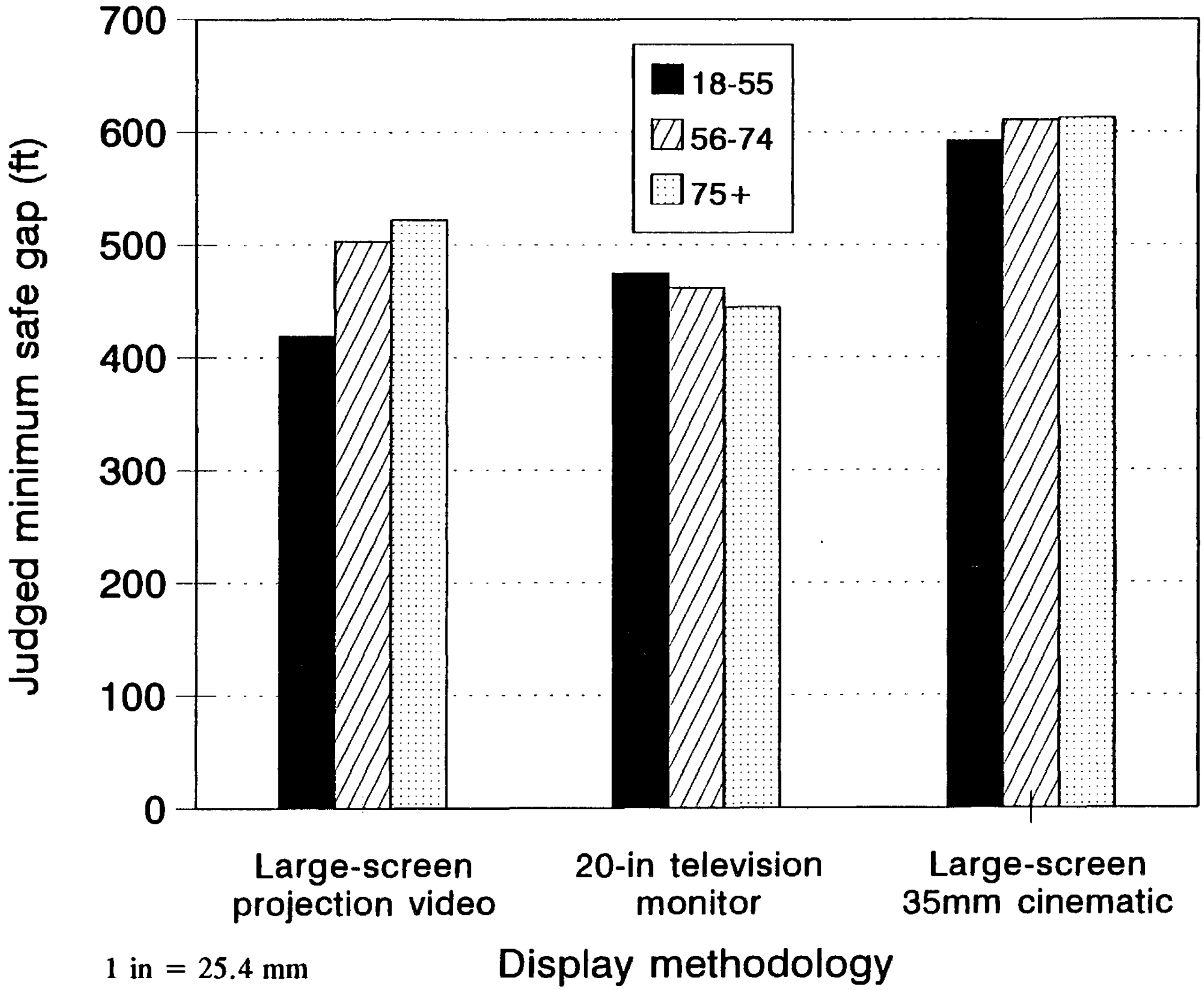
1 mi/h = 1.61 km/h
1 ft = 0.305 m

Figure 43. Judged minimum safe gap (ft) for stationary observers in three age groups to perform a right turn ahead of traffic maneuver.



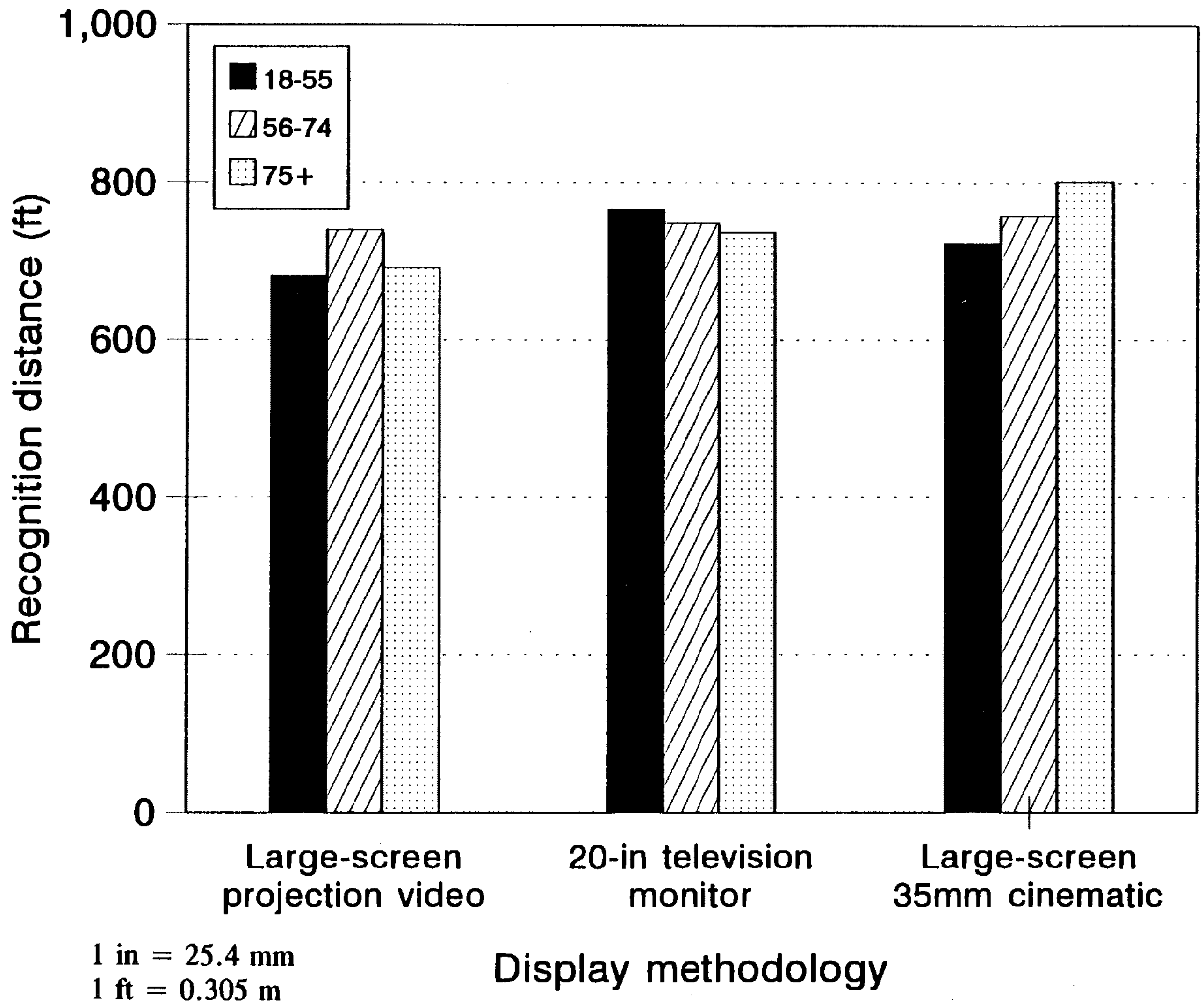
1 mi/h = 1.61 km/h
1 ft = 0.305 m

Figure 44. Target recognition distance (ft) for stationary observers in three age groups to perform a right turn ahead of traffic maneuver.



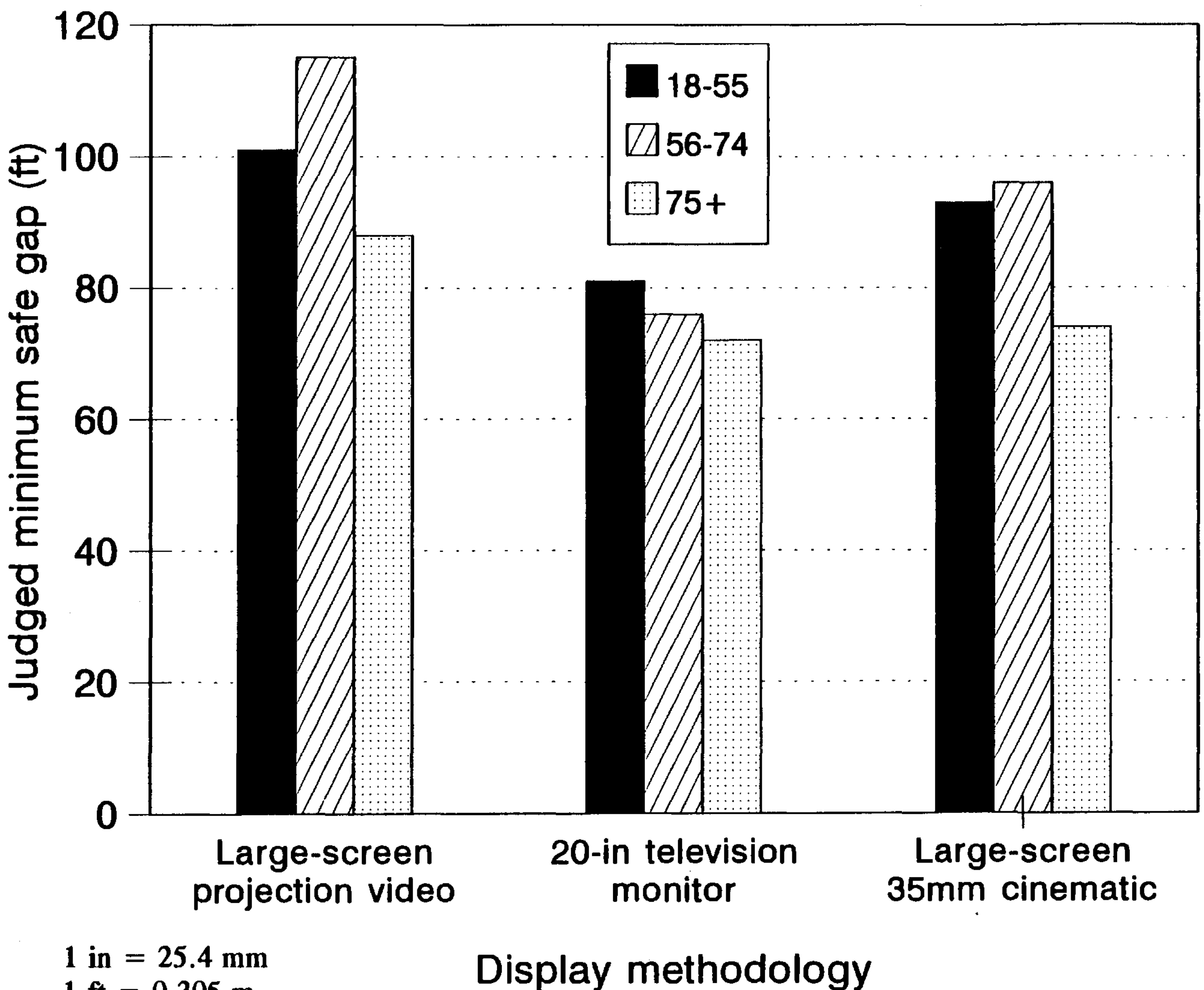
1 in = 25.4 mm
1 ft = 0.305 m

Figure 45. Judged minimum safe gap (ft) for stationary observers in three age groups to perform a freeway merge maneuver, when target approach speed equals 60 mi/h (96 km/h).



1 in = 25.4 mm
1 ft = 0.305 m

Figure 46. Target recognition distance (ft) for stationary observers in three age groups to perform a freeway merge maneuver, when target approach speed equals 60 mi/h (96 km/h).



1 in = 25.4 mm
1 ft = 0.305 m

Figure 47. Judged minimum safe gap (ft) for stationary observers in three age groups to perform a car following maneuver when target approach speed increases from 45 to 60 mi/h (72 to 96 km/h).

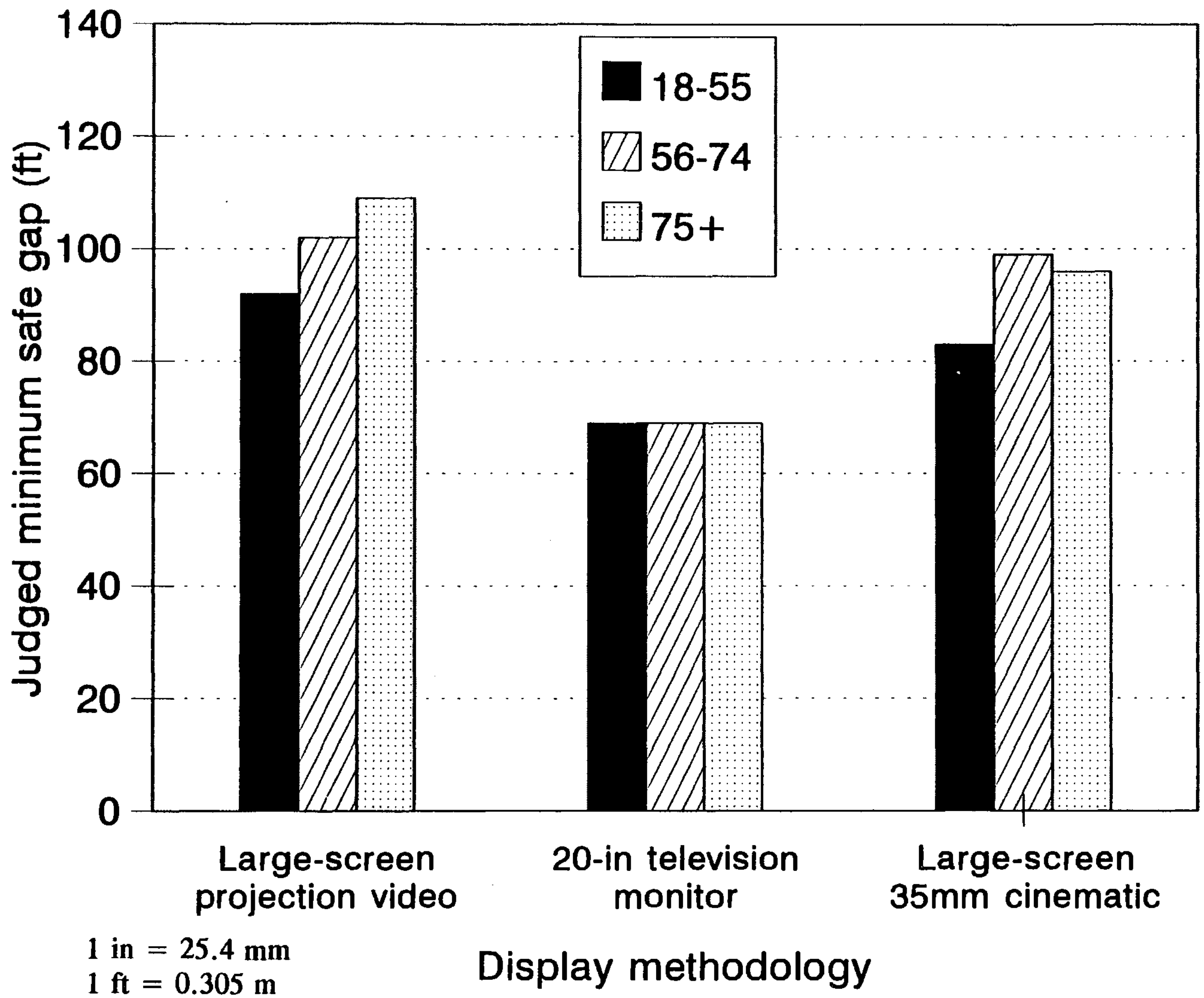


Figure 48. Judged minimum safe gap (ft) for moving observers in three age groups to perform a car overtaking maneuver when target approach speed equals 45 mi/h (72 km/h).

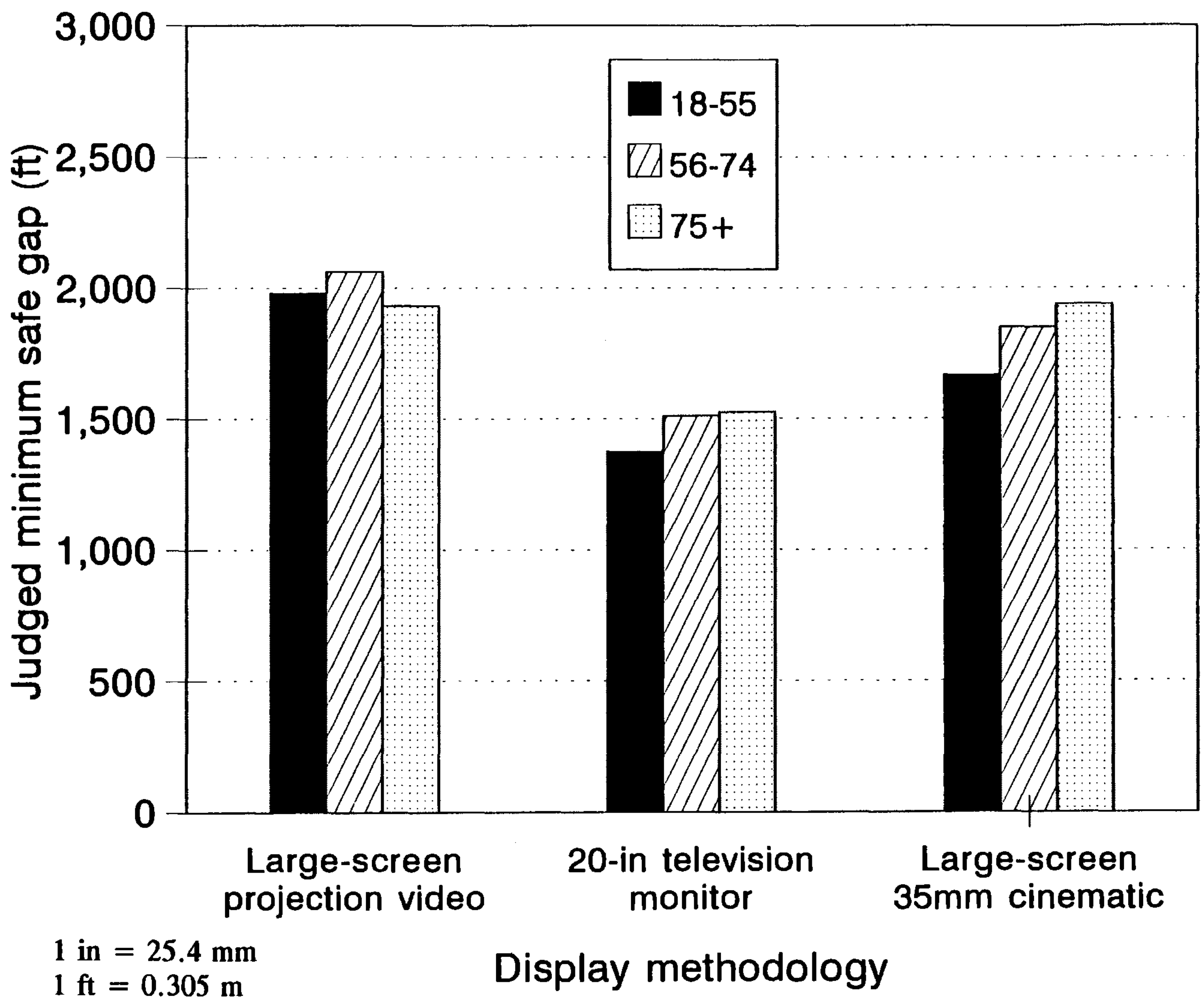
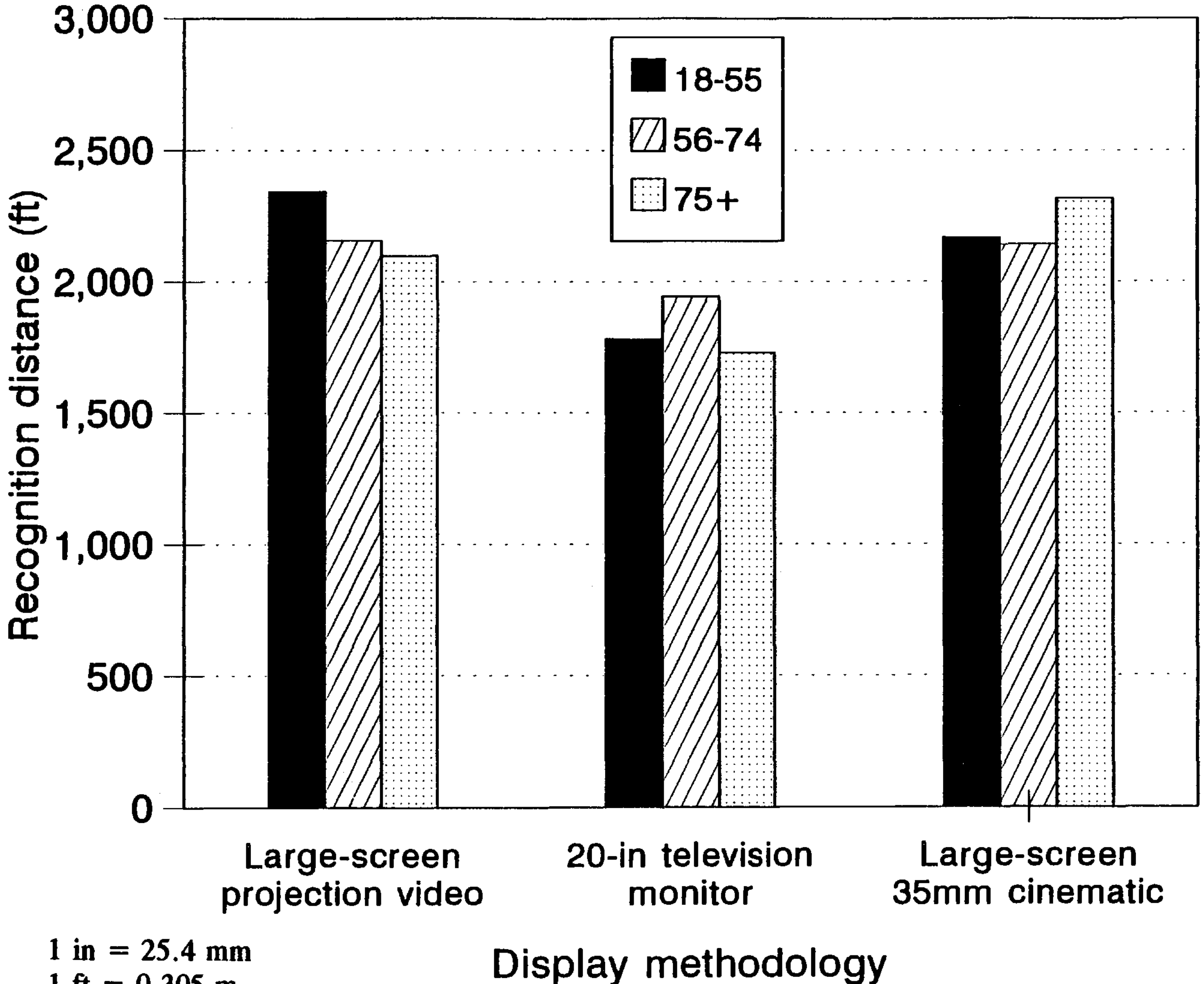


Figure 49. Judged minimum safe gap (ft) for <u>moving</u> observers in three age groups to perform a <u>passing</u> maneuver when target approach speed equals <u>45 mi/h (72 km/h)</u>.



1 in = 25.4 mm
1 ft = 0.305 m

Figure 50. Target recognition distance (ft) for <u>moving</u> observers in three age groups to perform a <u>passing</u> maneuver when target approach speed equals <u>45 mi/h (72 km/h)</u>.

Differences in target approach speed resulted in significant differences in both target recognition distance and the judged minimum safe gap for the left turn test conditions in these experiments, for all laboratory methodologies. Overall, increasing target speed led to significantly **shorter** minimum safe gap judgments ($F=9.57$; $df=3$; $p<.0001$) as well as shorter target recognition distances ($F=51.51$; $df=3$; $p<.0001$) using video projection to present test stimuli. For the television monitor data for this maneuver, the same pattern was observed: decreasing minimum safe gap judgments ($F=5.63$; $df=1$; $p<.02$) and shorter target recognition distances ($F=71.83$; $df=1$; $p<.0001$), with increasing target approach speed. With cinematic stimulus presentation, however, just the opposite results were demonstrated--i.e., significant **increases** in the judged minimum safe gap ($F=31.55$; $df=1$; $p<.0001$) and target recognition distance ($F=5.25$; $df=1$; $p<.03$) as target speed increased. In the field trials only the gap judgment measure was obtained; for these data, an increase in the judged minimum safe gap with increasing target approach speed ($F=14.28$; $df=1$; $p<.0009$) mimicked the trend observed in the cinematic data in the laboratory.

Most interesting were the significant interaction effects on gap judgment involving subject age group and target approach speed that were demonstrated for the video projection and television monitor methodologies in the laboratory, and for the controlled field trials. Using video projection to present test stimuli, the interaction effect was demonstrated as the judged minimum safe gap for young/middle-age drivers remained relatively constant across target speeds, while both the young-old and old-old drivers accepted **smaller** gaps as target speed **increased** ($F=4.95$; $df=6$; $p<.0001$). This identical pattern was also found in the television monitor data ($F=3.14$; $df=2$; $p<.05$). The results of the controlled field trials, however, differed markedly: the judged minimum safe gap of young/middle-age drivers increased along with target speed, while the responses of young-old and old-old drivers were insensitive to this independent variable ($F=4.49$; $df=2$; $p<.02$). It may be noted that the pattern in the cinematic laboratory data paralleled that observed in the field, but, at $p<.09$, failed to reach significance.

The results for the highway crossing gap acceptance data collection in these experiments paralleled the left turn maneuver results, in terms of age effects on the two dependent measures under the various laboratory stimulus presentation methodologies. Using video projection, the judged minimum safe gap for this maneuver increased with increasing subject age ($F=13.82$; $df=2$; $p<.0001$), while target recognition distance was not significantly affected. Using television monitor stimulus presentation, the same age effect was demonstrated at $F=5.97$ ($df=2$; $p<.004$), and increasing age also led to larger minimum safe gap judgments with cinematic stimulus displays ($F=6.14$; $df=2$; $p<.004$). A significant effect of subject age group on target recognition distance was noted only for cinematically-presented stimuli, with younger subjects again recognizing the target at greater distances than older subjects when this methodology was employed ($F=5.26$; $df=2$; $p<.008$).

For this maneuver, increasing approach speed of the oncoming target vehicle only resulted in significantly larger minimum safe gap judgments when test stimuli were presented cinematically ($F=8.54$; $df=1$; $p<.0048$). No main effects of target speed on gap judgment were demonstrated for the video projection or television monitor methodologies due to the interaction effects of age group and target speed, discussed in the following paragraph. At the same time, an opposite pattern of effects of target speed was shown for target recognition distance: significant differences were found using the video projection and television monitor methodologies, but not when the test stimuli were presented cinematically. As target speed increased, shorter target recognition distances were apparent in both the video projection ($F=8.29$; $df=3$; $p<.0001$) and the television monitor ($F=57.22$; $df=1$; $p<.0001$) data.

Significant interactions in subjects' minimum safe gap judgments for the highway crossing maneuver were demonstrated in two instances, reflecting an identical pattern of responses. This effect, observed in both the video projection ($F=4.08$; $df=6$; $p<.0007$) and the television monitor ($F=8.89$; $df=2$; $p<.0004$) data, showed that as target speed increased, the minimum safe gap judgments of young/middle-age drivers also increased. The gap judgments of young-old drivers did not shift significantly up or down; and the minimum safe gap judgments for the old-old group decreased sharply. It may be noted that shifts in gap judgments with changes in target speed were consistent within age group using the cinematic stimulus presentation methodology; thus, no interaction effect was found.

No controlled field trials were performed to assess gap acceptance for the highway crossing maneuver.

Turning to a consideration of the results when subjects judged the minimum safe gap to perform a right turn ahead of traffic onto a two-lane highway from a stationary position at an intersection, significant effects of age group were demonstrated for two of the three laboratory methodologies. Increasing subject age resulted in larger safe gap judgments using video projection ($F=6.17$; $df=2$; $p<.003$) and television monitor ($F=3.53$; $df=2$; $p<.03$) displays, while responses on this dependent measure did not differ significantly with cinematic stimulus presentation. However, with cinematic stimulus presentation, young/middle-age subjects recognized the target at significantly greater distances than older subjects ($F=7.68$; $df=2$; $p<.001$), while responses on this measure did not differ significantly as a function of subject age group using the video projection or television monitor methodologies. No significant effect of age group on gap judgments for this maneuver were documented by the GLM analysis.

The effects of target speed were more widespread across stimulus presentation methodologies for this maneuver, though not always manifested in the same pattern of results. Increasing target approach speed resulted in **shorter** minimum safe gap judgments using video projection ($F=62.82$; $df=3$; $p<.0001$) and television monitor ($F=139.94$; $df=1$; $p<.0001$) displays. At the same time, target recognition distances also decreased for both video projection ($F=71.23$; $df=3$; $p<.0001$) and television monitor ($F=120.53$; $df=1$; $p<.0001$) stimulus presentation. Using the cinematic methodology, however, the judged minimum safe gap **increased** with increasing target approach speed ($F=24.47$; $df=1$; $p<.0001$), while target recognition distance was not significantly affected by changes in this independent variable.

It should be noted that the trend in the gap judgment data in the controlled field trials paralleled that observed using the cinematic methodology in the laboratory--i.e., increasing target approach speed generally resulted in larger minimum safe gap judgments. This effect failed to reach significance at $p<.08$, however, due to exaggerated variability among both older driver groups. (Target recognition distance was not measured in the controlled field trials.)

Only a single interaction effect was demonstrated for the right-turn-ahead-of-traffic maneuver data. Using the video projection methodology for stimulus presentation, a significant interaction ($F=3.49$; $df=6$; $p<.003$) between age group and target speed on the gap judgment measure was indicated: older subjects' minimum gap sizes grew consistently smaller as target speed increased, while younger subjects' responses did not change significantly across levels of this variable.

The freeway merge maneuver data, obtained only under laboratory conditions in these experiments, was more difficult to interpret. The judged minimum safe gap increased with increasing driver age using the video projection and cinematic display methodologies, while older drivers' safe gap judgments were smaller than younger drivers' judgments when stimuli were presented on the television monitors. Of these effects, only the differences evident in the video projection data approached statistical significance ($p < .06$). For the target recognition distance measure, the performance of all age groups was roughly equivalent when test stimuli were presented using the video projection and television monitor methodologies. With cinematic stimulus presentation, however, older subjects' responses indicated that they recognized the target vehicle at significantly **greater** distances than younger subjects ($F=8.00$; $df=2$; $p < .0008$). One possible explanation for this counterintuitive finding may be a confusion expressed by some subjects, as to which of several cars visible on the freeway mainline was the target vehicle for this trial type.

Only minimum safe gap judgments were performed for the freeway exit/weave maneuver, and only video projection was used to present the test stimulus. As a reminder, the progress of a moving observer was frozen on the freeway mainline near the gore of an entry ramp, along which another vehicle was accelerating toward a merge. The observer looked over his/her right shoulder to watch the other (target) vehicle's approach, and indicated the last point at which it was safe to weave in front of the target vehicle to exit the freeway. No significant differences were demonstrated in this data, as mean performance was nearly identical across groups and standard deviations--while slightly exaggerated for the older driver samples--remained tight with respect to mean values on the gap judgment measure.

Significant differences in the judged minimum safe gap for car following were noted for two out of three of the laboratory display methodologies. The safe gap judgments of young-old drivers increased somewhat, relative to the younger driver group, then a sharp **decrease** in this measure was demonstrated by the old-old subjects, using both the video projection ($F=4.11$; $df=2$; $p < .02$) and cinematic ($F=5.32$; $df=2$; $p < .007$) laboratory methodologies. Responses of the respective age groups exhibited the same pattern, but were clustered more tightly together using television monitor stimulus presentation.

Target recognition distance was not measured and no controlled field trials were performed for the car following maneuver.

In an examination of the car overtaking data, a trend toward larger minimum safe gap judgments with advancing driver age was clearly demonstrated in the video projection and cinematic trials, but these differences failed to reach significance. The mean responses of the respective age groups were identical, and standard deviations were similar, across the three laboratory display methodologies for this maneuver.

Target recognition distance was not measured and no controlled field trials were performed for the car overtaking maneuver.

Finally, the passing maneuver results showed only small and nonsignificant differences between age groups, for both the minimum safe gap judgment and target recognition distance measures. Again, no controlled field trials were performed for this maneuver.

Discussion. While reiterating that the present research objective was to determine **relative** differences in gap acceptance as a function of the included independent variables, an initial topic of interest is the evaluation of subjects' gap judgments in relation to an absolute "safe vs. unsafe" standard of performance. Accordingly, a post-hoc examination of responses performed in the field for the left and right turn maneuvers was conducted, using conservative assumptions to calculate stopping sight distances for the through (conflict) vehicle. Even though an avoidance maneuver by the through vehicle may be more likely in response to a late ("unsafe") turning movement, a gap that allows braking to a full stop covers all contingencies in this situation, and thus defines the most conservative criterion for a "safe" gap.

On average, **none** of the driver groups in this research accepted unsafe gaps for the (turning) maneuvers examined under controlled field conditions, based on calculations of the braking sight distance for the oncoming (conflict) vehicle. These calculations included a brake reaction component and a stopping distance component. At a 30 mi/h (48 km/h) approach speed for the through vehicle, on a dry, level roadway where the coefficient of friction is assumed to be 0.65, the actual braking distance is estimated to be 46 ft (14 m). At a 60 mi/h (96 km/h) approach speed under the same conditions, braking distance would be approximately 185 ft (56 m). A very conservative estimate for the braking reaction component is 2.5 s, which could apply if the oncoming vehicle was also driven by an older individual. At 30 mi/h (48 km/h) this component adds 110 ft (34 m), and at 60 mi/h (96 km/h) it adds 220 ft (67 m), resulting in overall stopping sight distance requirements for the oncoming vehicle of roughly 156 ft (48 m) and 405 ft (124 m) at the lower and higher speeds, respectively.

Inspection of the standard deviations for judged minimum safe gap for the left turn and right turn maneuvers in the field (see tables 37 and 38) reveals that roughly the bottom third of the oldest group accepted a gap shorter than the calculated braking sight distance requirement for the oncoming vehicle at a 60 mi/h (96 km/h) approach, for both maneuvers. However, since the youngest group responded similarly (although only for the left turn maneuver), this data does **not** provide compelling evidence of diminished response capabilities of older drivers--in any **absolute** sense--in these traffic situations. What must again be emphasized is that it was never **intended** in the present research design to test absolute gap acceptance distances. Indeed, the obvious demand characteristics of the test protocol used in this project militate strongly against valid, absolute gap judgments.

Thus, the focus remains on the relative ability of older vs. younger drivers to accurately perceive the position and motion of conflict vehicles in specific traffic situations, as a presumed antecedent to appropriate maneuver decisions. Where a **relative** disability is indicated for older drivers--even though in the majority of cases an accident would not be a likely result--it was a clear objective in this project to develop countermeasure options, as presented in the following chapter.

To proceed with this discussion, interpretation of findings in the gap acceptance experiments is necessarily maneuver-specific, except to the extent that broad patterns in subjects' responses across several different maneuvers suggest systematic effects of the varying laboratory simulator displays. The three display methodologies, as previously noted, presented identical views of the same target (oncoming) vehicle in the same driving situations, to a common test sample. A limited field validation of the laboratory findings was also provided by work completed in this task, for two maneuvers of greatest interest from the perspective of demonstrated age differences in multiple accident data bases--left turns across traffic and right turns into traffic.

One recurrent finding deserving emphasis is that the perceptual and cognitive functions underlying maneuver decisions did **not** reflect significantly different capabilities for older and younger drivers in a number of instances in this research. For the passing maneuver on a two-lane highway, and for the car overtaking maneuver--where subjects judged the minimum safe following distance as they overtook a slower lead vehicle from the rear--there was no age effect found. However, it was also observed that age-related differences in these data were often accompanied by high within-group variability, particularly for older drivers. The possibility thus exists that differences that failed to meet criteria for statistical significance reflect real differences in drivers' capabilities, at least for average and below-average performers, which are operationally important in defining the needs of the overall population of highway users.

The passing gap acceptance data are instructive in this regard. The mean minimum safe gap for this maneuver as judged by the young/middle-age group was only 150 ft (45.7 m) smaller than the oldest group's judgment [1,376 ft (419 m) vs. 1,526 ft (465 m)] using television monitor stimulus presentation, and was but 82 ft (25 m) shorter than the farthest older driver mean response level using video projection [1,980 ft (603 m) vs. 2,062 ft (628 m)]. Size and motion cues were of course highly unrealistic with the TV display, though, and the target image was noticeably blurred at these response distances using video projection. When test stimuli were presented cinematically, showing clear images in correct perspective, the mean minimum safe gap judgments for the passing maneuver for the three age groups were 1,668, 1,850, and 1,938 ft, (508, 564, and 591 m) respectively, moving from youngest to oldest. A regular increase in the standard deviations in subjects' responses with advancing age was also observed (see table 32). Taking the demonstrated variability of these data into account, it is apparent that a substantial fraction of subjects 75+ years of age indicated a need for gaps that greatly exceeded the judgments of the young/middle-age subjects.

The results were similarly equivocal for the freeway merge and freeway exit/weave maneuvers, though without the regular trends in mean response magnitudes and variability within the group that were helpful in interpreting the passing maneuver data. In addition, as noted earlier there were methodological difficulties with each of these sets of test conditions. Fully dynamic test scenarios with unambiguous, clearly-perceived target/conflict vehicles appear to be necessary to obtain meaningful measures of driver age differences for these maneuvers in the laboratory. Judgments made under actual operating conditions would be most desirable. Based on the preliminary findings, anecdotal data describing age-related differences in freeway merging behaviors appear at least as likely to result from a documented decrease in the ability to rapidly shift visual attention between left rear and forward search areas--reflecting a lack of physical flexibility, cognitive flexibility, or both--as from age differences in gap acceptance.

The car following results indicated that the oldest (75+ years of age) test subjects in this research judged the minimum safe gap between themselves and a lead vehicle to be significantly **smaller** than did the young/middle-age or young-old drivers, using both video projection and cinematic stimulus presentation. These trials began with the following (subject's) vehicle virtually on the rear bumper of the lead vehicle, both traveling at 45 mi/h (72 km/h); then, the lead (target) vehicle increased its speed to gradually pull away from the subject, who responded when a safe following gap was reached. If this pattern of responses could be confirmed through field data collection under representative conditions, it would--coupled with widely-observed decrements in choice reaction time among older adults--describe a serious safety problem.

The most critical current area of concern for older drivers, in light of available accident data stratified by driver age and traffic situation, is performing left turns at intersections. In this research, younger drivers waiting at an intersection on a two-lane highway to turn left ahead of oncoming traffic consistently selected shorter minimum safe gap distances than older drivers, across as many as four different target vehicle approach speeds. The proportional change in gap judgment from one target speed to another differed markedly from one age group to another, however, and was also clearly sensitive to the method of stimulus presentation used.

The left turn maneuver test scenario was included in the limited field data collection in these experiments. Most notable was the constancy of the exaggerated gap distances evidenced by both older driver groups, at 30 mi/h (48 km/h) and at 60 mi/h (96 km/h) target approach speeds, relative to the young/middle-age sample: the mean response of the 56-74 age group changed only 1.5 percent (higher), and the 75+ age group only 3.5 percent (lower), from the lower to the higher speed. The 18-55 age group, by comparison, judged the minimum safe gap to proceed with a left turn under these circumstances to be **25 percent larger at 60 mi/h (96 km/h) than at 30 mi/h (48 km/h)** in the controlled field trials. This apparent insensitivity of older drivers to varying approach vehicle speeds raises important operational questions to be addressed in the discussion of countermeasures to follow in the next chapter.

The pattern just described in the field validation data for the left turn maneuver was approximated in the cinematic data as well. As target speed increased from 30 to 60 mi/h (48 to 96 km/h), the mean safe gap judgment of the 18-55 age group jumped 23 percent; at the same time, the mean gap judgment distances of the young-old and old-old groups increased just 13 percent and 6 percent, respectively. Using video projection for the simulated driving display produced a dramatic shift in subjects' responses, however. Across the same target speeds [30 and 60 mi/h (48 and 96 km/h)], the young/middle-age drivers' judgments of the minimum safe gap to turn left ranged from 480 to 487 ft (144 to 146.1 m)--i.e., a variability of under 2 percent. Meanwhile, the mean response levels of the 56-74 and 75+ age group declined in a linear fashion as target speed increased, dropping by 19 percent and 14 percent, respectively, from the slowest to the fastest target approach speed. And an inspection of figure 39 reveals trends in the television monitor data comparable to that observed using the video projection method.

Based on these results, only the data obtained using the cinematic laboratory methodology can be considered valid with respect to the field measures, but this conclusion, too, must be qualified. The absolute magnitudes of drivers' responses for all cells in the cinematic trials test conditions exhibited mean values consistently higher than were observed for corresponding cells in the controlled field trials. For isolated cells the results obtained using other methodologies--e.g., television monitor--produced closer matches to the field data, in terms of absolute magnitude of judged minimum safe gap; but the degree of conformity of the overall pattern of responses for shared test conditions between the field trials and each laboratory methodology is, in the author's opinion, the most appropriate validation criterion.

The other set of test conditions that afforded direct comparisons between subjects' responses in the laboratory and under field conditions pertained to the right-turn-ahead-of-traffic maneuver at an intersection on a two-lane highway. When target approach speed increased from 30 to 60 mi/h (48 to 96 km/h), the changes in mean safe gap judgments by subject age group for this maneuver were as follows:

Methodology	Group	Percent Change	Direction
video projection	18-55	30	decrease
	56-74	18	decrease
	75+	29	decrease
television monitor	18-55	30	decrease
	56-74	28	decrease
	75+	33	decrease
cinematic	18-55	9	increase
	56-74	13	increase
	75+	13	increase
controlled field	18-55	41	increase
	56-74	1	increase
	75+	7	increase

These results are less clear-cut than were the left turn data, but some interesting contrasts can be drawn among the various display methodologies. The trend of increasing minimum safe gap judgments with increasing target approach speed for those subjects presumably without diminished motion perception capabilities--i.e., the 18-55 age group--was reinforced strongly in the controlled field trials, and to a lesser extent when stimuli were presented cinematically. The large and equivalent **decrease** in such judgments as target speed increased using video projection and television monitor methodologies is problematical.

Next, with shifts in mean gap judgment of only 1 percent and 7 percent for the young-old and old-old groups, respectively, across target speed conditions in the field, the conclusion that older drivers are relatively insensitive to this variable is supported for this maneuver as well as for the left turn maneuver. This pattern indicating age-related differences in sensitivity to target approach speed was not demonstrated among any of the laboratory data sets for the right-turn-ahead-of-traffic maneuver, however. Even so, it deserves mention that for these laboratory data, only those obtained using the cinematic methodology described the expected relationship of larger safe gap judgments with higher target approach speeds.

The remaining data collected in these experiments addressed subjects' judgments of the minimum safe gap to cross a two-lane highway from a stationary position at an intersection. As expected, the 18-55 age group consistently accepted a smaller gap than older drivers, and increasing gap distances were linear with increasing age at all speeds and under all display methodologies. Still, while the faster target approach speed resulted in larger gap distances for every age group using cinematic stimulus presentation, the oldest (75+ years of age) group demonstrated the unanticipated tendency to systematically **shorten** their minimum safe gap judgment when the intersecting conflict vehicle was approaching at 60 vs. 30 mi/h (96 vs. 48 km/h), with the television monitor and video projection displays.

This outcome, and other contrasts between the mean response levels for each age group under varying test conditions, allow some preliminary generalizations about the systematic influences of stimulus attributes associated with each display methodology used in this research. The most problematic discrepancy between laboratory and field measures (for the same subjects viewing the same test stimuli) is the decline in judged minimum safe gap by older drivers when a conflict vehicle approached at a faster vs. a slower speed. This phenomenon repeatedly characterized data obtained using two of the display methodologies--video projection and television monitor--but not the third (cinematic projection). An obvious question is the extent to which these simulation techniques impose limitations on the ability of observers of different ages to process motion cues to extract reliable information about the speed-distance relationships of other vehicles, relative to their own position.

Prior motion perception studies identified in the literature review support the assertion that older adults base gap acceptance decisions primarily--or exclusively--on the perceived distance of a conflict vehicle, while younger individuals are better able to incorporate information about vehicle speed into their gap sufficiency judgments for a given maneuver. The relative insensitivity of both older driver groups to varying target approach speeds in the controlled field trials, particularly for the left turn maneuver, is consistent with this interpretation. These data also confirm that the young/middle-age group was able to shift their gap acceptance to take target speed into account, in a manner consistent with expectations for safe performance of this maneuver.

Since it must be assumed that display artifacts are absent from the controlled field data, the observed pattern of responses for younger and older drivers can be interpreted as reflecting the diminished capability of older subjects to process motion cues under conditions where there is no deficiency of information in the image. Where a deficiency of spatial information exists, it might be expected to also result in distortions in the judgments of younger subjects. Specifically, the loss of high frequency spatial cues might be expected to level performance across age groups, because younger subjects with the capability to use such information do not have it available to them.

The similarity of response patterns in the cinematic data to those in the field data suggest that the film methodology provided sufficient information for valid gap judgments, while differences associated with the video projection and television monitor data indicate some deficiencies in the information provided by these stimulus presentation methods. The key differences in the attributes of each display type, described earlier in greater detail, are: a loss of realistic target size and perspective cues with the television monitor NTSC signal, and a loss of image resolution (high spatial frequency information), but preservation of correct perspective with video projection, while cinematic stimulus presentation sought to preserve nominal values for these attributes.

Finally, the smaller minimum safe gap judgments of the older subjects using the video projection and television, but not the cinematic laboratory methodology, may reflect a floor effect in (spatial) information processing capability for a degraded (low resolution) image. Logically, more processing effort will be required to reach a confident judgment regarding target size when viewing a diffuse image vs. a sharply-defined image. The instantaneous processing of size cues for a diffuse target should therefore be interfered with to a greater extent by increasing target speed, and for observers with diminished motion perception capabilities, a minimum sampling interval may be reached. This increased processing difficulty alleged to occur at higher speeds could produce a lower target recognition distance for degraded images, and the minimum sampling interval--the reputed information processing floor effect--would correspondingly result in a lower gap judgment distance at 60 mi/h (96 km/h) than at 30 mi/h (48 km/h). While target recognition distance also was reduced for the young/middle-age subjects using the video projection and television monitor displays, their hypothesized greater efficiency in spatial information processing presumably compensated to a degree for this limitation in the availability of relevant spatial cues.

With the cinematic display, target recognition distance did not decrease for any age group from the lowest to the highest approach speed. Thus, absent significant image degradation, the spatial information drivers seek for gap judgments was available at a distance sufficiently beyond the perceived minimum safe gap that adequate processing time was afforded to all subjects, i.e., no floor effect of the sort suggested above has occurred.

Under these circumstances, it makes sense that observed differences in mean response magnitude for gap judgment between groups can be accounted for strictly in terms of individual-related diminished capabilities, as opposed to stimulus-bound factors.

The points raised in this discussion lead to the conclusion that valid measurement of age differences in vehicle motion perception and associated maneuver decisions in the laboratory depend upon the presentation of a test stimulus that matches to the greatest extent possible the realism of the real-world performance context to which results are to be generalized. To understand the relationships between driver age and operational factors such as the speed of an oncoming vehicle, the preservation of high image resolution plus correct size and perspective cues offers clear advantages in driving simulation research.

COUNTERMEASURES IDENTIFICATION

INTRODUCTION

Older drivers have not been shown in this research to experience problems with overestimation of time to collision (relative to younger drivers). Moreover, they have been shown to have the ability to detect oncoming vehicles at distances adequate to permit safe turning, merging, and highway crossing maneuvers. However, it does appear that older drivers are relatively insensitive to the speed of oncoming vehicles, which may lead to errors when performing maneuvers such as a left turn across traffic.

Notwithstanding the findings referred to above, and regardless of the nature of physiological/psychological deficits that older drivers may or may not have, it is clear that older drivers are consistently overrepresented in turning accidents at intersections, as analyses of data from multiple jurisdictions have shown. Indeed, this may be the single most important problem to be addressed in improving safety and mobility for this group of highway users. Therefore, the present emphasis is on the amelioration of problems at signalized (and some signed) intersections--especially for left turn maneuvers.

PROBLEM DEFINITION

There are two aspects of turning accidents that need to be addressed: first, the turning driver needs some sort of reinforcement that a potentially hazardous maneuver is being attempted; and second, the oncoming drivers need to be alerted that another driver may attempt a maneuver that crosses their path. A typical left turn accident scenario--based on the analyses of Michigan and Pennsylvania data bases conducted in this research--has an older driver (perhaps in the poorer-performing segment of the population with respect to detecting oncoming vehicles and estimating time-to-collision) turning left across the path of a higher speed, overly confident younger driver. A related scenario can be constructed for right turns (after a stop) by older drivers into a stream of fast-moving (through) vehicles. While these are not the only troublesome scenarios (or causes for accidents) for older drivers, they are clearly consistent with the problems that reported accident analyses have identified.

These scenarios suggest two different types of highway safety countermeasures:

- Make the turning driver more aware and careful before and during the maneuver--either with or without the provision of explicit cues regarding the safety of the maneuver.
- Make the oncoming, typically through drivers, more aware of the potential for a conflict ahead with a turning vehicle--slowing them down, focusing their attention on the potential conflict, or both.

COUNTERMEASURES

In the following discussion, a range of countermeasure options for the amelioration of problems associated with turning movements at intersections is presented. The options, addressing both the turning and through drivers, range from "high-end" technological deployments (e.g., vehicle-activated warning signs) to "low-end" solutions such as simple advisory (warning) signs. The countermeasures are discussed in terms of likely effectiveness (engineering judgment), cost, safety, traffic flow, and liability (e.g., a lawsuit for a high-tech sign failure). A single urban-suburban arterial intersection is used throughout to illustrate typical implementation, cost, and the other issues just noted.

From the outset, it should be noted that there are numerous instances where intelligent vehicle/highway system (IVHS) technology could be hypothesized to have a positive ameliorating effect on the safety problems being discussed--e.g., collision-avoidance sensing devices. Such solutions are not discussed here, primarily because such technology will not be available to highway users for some time (and may never be to some socio-economic groups such as older persons on limited fixed incomes). In any event, availability of IVHS technology does not preclude the use of the countermeasures discussed here.

The countermeasures discussed below are grouped according to the maneuver the driver would be attempting to undertake--i.e., turning and through movements--and by level of required technology.

TURNING DRIVERS

The left turn maneuver is generally considered to be more dangerous than turning right and is given primary attention below. Moreover, many countermeasures that can be developed for left turn maneuvers can be modified slightly to provide similar benefits for the right turn maneuvers. Thus, in most instances below, the left turn situation is discussed first and then the modifications that would be necessary for the right turn movement are presented.

Generally speaking, there are four different approaches to controlling potential conflicts associated with left-turning traffic: (1) eliminate the conflict by prohibiting the turning movement; (2) eliminate the conflict by protecting the turning movement with a signal phase; (3) substantially change the intersection operating pattern through changes in the geometry; and, (4) provide additional information to drivers when the turn is permitted.

The first two approaches have an absolute effect on the problem by eliminating it. Both, however, have capacity and more general traffic flow problem issues associated with them. Providing for the protected left typically reduces the overall capacity of the intersection. Prohibition, on the other hand, results in either migration of the problem to the next available left-turn opportunity or introduces travel delay associated with selection of an alternative route (e.g., three right turns). Neither of the outcomes of the prohibition treatment would seem to necessarily result in a safer outcome for older drivers. (Is making a permitted left at a signalized intersection better or worse from a safety perspective than making three successive right turns at possibly unsignalized intersections?)

Changes in the intersection geometry, the third approach listed above, can also be used to effectively eliminate the conflict of left-turning vehicles with opposing, oncoming vehicles. The advantage of this alternative is that while eliminating the conflict, the driver's desired change in direction is still accommodated. Two typical treatments are a "jug-handle" turn; and a "directional cross-over." The jug handle prohibits left turns at the intersection per se, while requiring the driver who wishes to make the left to make a right turn onto the "jug-handle" ramp, then merge with traffic on the cross street. The directional cross-over also prohibits left turns at the intersection, but allows the driver who wishes to make a left to cross over the median just beyond the intersection (essentially reversing directions) and then make a right turn on the cross street. In this latter case, the crossing maneuver from the median has to be protected by signalization.

While both of the geometric changes have been proven to be effective in certain situations, they are clearly high-cost alternatives and require significant right-of-way. Indeed, the directional cross-over is only useful if there is a substantial median present (e.g., on a boulevard). Moreover, it can be argued that these are relatively complex movements and may be confusing to the target group (and others). Their efficacy for the target group is unknown and their general effectiveness has been questioned by some practitioners. Because of the high cost of these alternatives and some questions about their effectiveness for specific driver groups, they are not given any additional consideration here.

The countermeasures proposed below are generally directed to the fourth approach, that is, to ameliorate the safety problems associated with a driver's attempt to make a permitted (as opposed to protected) turn through use of traffic control device countermeasures.

High-End Solutions

"High-end" solutions require deployment of some sort of "smart" equipment, such as vehicle-activated signs. Typically, some sort of computer-like control mechanism is required. Although not discussed, IVHS-related technology would fall into this category.

Flashing or Illuminated Signs with Positive Messages. It has long been established that flashing signs, when used in moderation, are effective in getting a motorist's attention and eliciting a positive response, especially when the message is positive and unequivocal in nature--e.g., VEHICLE ENTERING WHEN FLASHING. (Note that literal sign messages are given in all capitals here.) In this vein, one potential countermeasure for the left-turning driver (on approach 2 in figure 51) is a sign at the diagonally opposite corner (position A in figure 51). The sign could take one of two forms: either a flasher-augmented advisory plate with a message such as DO NOT TURN WHEN FLASHING; or a blacked-out message sign that is not legible unless the message is appropriate. Either message would provide the left-turning driver with gap acceptance information: when it is not lighted, it is acceptable to turn; when it is lighted, the turning maneuver should not be attempted. However, the flasher-augmented sign would also have to be in the flashing mode whenever the signal is red (for approach 4), otherwise the signal and the sign would give conflicting messages during that phase.

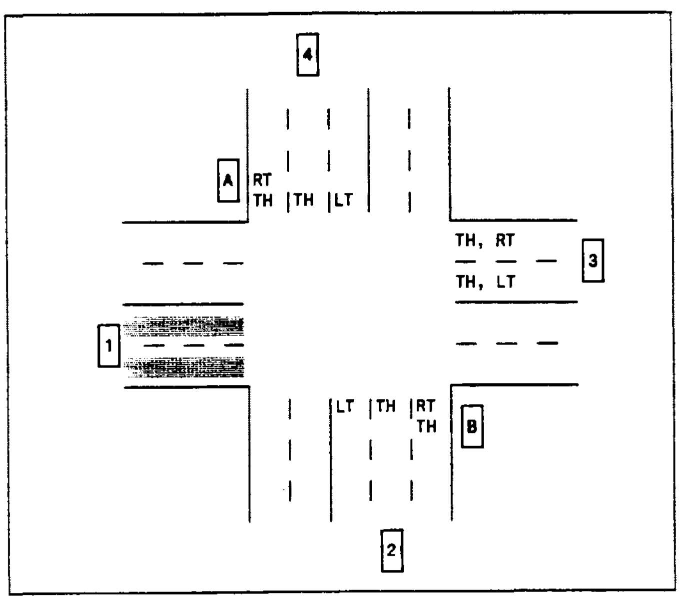


Figure 51. Typical intersection for countermeasure deployment for turning vehicles. [Note that boxed numbers refer to the approach (e.g., approach 1) while the boxed letters are sign deployment locations referred to in the text.]

Such a sign would require upstream detecting devices and a modest controller of some sort for the opposing approach (approach 4 in figure 51). The deployment would require logic for detecting simple presence of a stationary vehicle on the opposing approach near the stop line and calculating the speed of any vehicle moving toward the stop line. While the logic for displaying the message is conceptually simple enough for deployment, there would likely be operational and liability-related problems. Operationally, the logic would have to be conservative (in terms of the gap in the traffic and the allowable speed of the through vehicle) to ensure safety for virtually all drivers. Under high volume conditions with briskly moving traffic, it is easy to conceive of situations where the sign would be constantly illuminated. Moreover, the liability for either failure per se or perceived failure (the first left-turning motorist involved in a crash) would be quite high. Unlike ramp-metering signals and logic that merely release motorists on a ramp (no guarantee of safety), the proposed device implicitly guarantees safety. Thus, the message would have to be tempered (e.g., LEFT TURNS USE CAUTION) and some of the effectiveness of the sign is lost. These problems notwithstanding, such a countermeasure might have application at isolated signal-controlled intersections with relatively low volumes or even STOP-controlled intersections in rural areas.

An alternative, and less emphatic, message that would have a lower likelihood of tort liability problems would be the simpler, WATCH FOR ONCOMING VEHICLES, without a reference to flashing lights--however, the sign might only flash when vehicles are sensed. The failure condition of the sign (no lighted sign) does not imply that there are no vehicles approaching--it's simply not lighted.

Still another alternative would be a message similar to the one just noted that provides some additional information about the nature of the oncoming vehicle--e.g., HIGH-SPEED ONCOMING VEHICLE, FAST VEHICLE APPROACHING, or HIGH-SPEED VEHICLE APPROACHING. The key question to be answered concerning this sign would be whether turning motorists understand the message well enough to adjust their maneuver. For example, would the motorist simply hurry up and make the turn (a potentially hazardous response) or wait for the oncoming motorist to pass (the desired response). It is also necessary to determine the necessary threshold for a fast (or high-speed) vehicle--any vehicle traveling in excess of the speed limit seems reasonable. The liability issue would seem to be largely avoided with these options, with the possible exception of an oncoming vehicle that speeds up appreciably just after crossing--the turning driver is thus exposed to a fast vehicle that the system did not detect. Note that the same set of sensors could be used to both warn the turning driver and the through driver (see discussion below in connection with the through driver).

Again, it should be pointed out that in relatively heavy, fast-moving traffic (e.g., on a suburban arterial), the possibility exists that the sign might be continuously lighted. Thus, it may be that the most positive use of such vehicle-activated devices would be for relatively isolated signal-controlled intersections. A volume guideline should be developed for such signals--for example, opposing through (non-turning) volumes with 15-s average headways, which translates to 250 vehicles (or so) per lane per hour.

Implementation for one approach (e.g., information gathered on approach 4 and displayed on a sign at position A for left-turning vehicle on approach 2) would include three loops (near stop line for presence and an upstream speed trap), a controller with adjustable logic, and a lighted or flasher-augmented advisory sign. Costs for installation are estimated at $4,000 to $5,000.

If left turns were allowed on all approaches, similar costs would be required for all approaches. As noted earlier, a similar countermeasure can be developed for right turns into traffic. If the signs were implemented for all turns, the overall costs could run as high as $40,000 (the approximate cost of a fully-activated traffic signal deployment). At this level, the signing and lighting for the intersection would be extremely complex for any motorist--there would simply be too many signs and signals.

Mid-Range Solutions

"Mid-range" solutions are those that do not require any "intelligence" to be incorporated into the signs themselves--e.g., continually lighted signs and other improvements that can be achieved at a modest cost. These include traffic control devices, which either supplement the messages already being conveyed by the existing devices or provide some additional information to the motorist.

Supplementary Signal Heads at Driver's Eye Level. In several European countries, standard signal installations are supplemented with additional, smaller heads at the driver's eye level. These signal heads operate in unison with the regular signals and act to simply reinforce the standard signal head message when all heads are visible. They also present a positive, visible cue when the standard signal is partially obscured (e.g., the standard signal head is directly overhead or on a post near the stop line and not visible when a vehicle is at, or slightly over the stop line).

In the interest of providing additional cues to turning drivers (especially those who might use the yellow interval to turn), similar signal heads could be placed diagonally opposite the left-turning driver (position A in figure 51) or on a median island to the turning driver's left if one is present. An additional head to the right of a right-turning driver would serve a similar purpose for that maneuver (position B in figure 51). In addition, the additional signal heads could be further supplemented with simple advisory plates with messages such as LEFT TURNS WITH CAUTION or WATCH FOR VEHICLES FROM RIGHT (for left- and right-turning vehicles, respectively).

The cost of installing a single supplementary signal head should be on the order of $1,500 to $2,000, with a supplementary advisory plate adding an additional $100. If the treatment was required for all turns, the costs would be on the order of $13,000 to $17,000.

This device brings the signal message and the cautionary message of the sign down to the same horizontal plane as the oncoming vehicles, making it easier for the motorist to have access to all of the information required to complete the turning maneuver safely. Moreover, the information being provided does not lose any effectiveness if the treatment is undertaken in several locations. Finally, the signals and signs are relatively unobtrusive (in comparison with flashing beacons, for example)--an advantage in any mixed-use urban/suburban area. If the intersection is spatially large however, the signal head on the diagonally opposite corner may be difficult to find visually for the turning motorist.

Flasher-Augmented Warning Devices. There are a variety of messages that might also be appropriate for providing a reminder to the turning driver to watch out for potential conflicts. In this instance, the devices are augmented with continuously flashing beacons. These are all directed toward encouraging the turning driver to double-check to make sure that he/she can safely complete the turning maneuver. A variety of messages are reasonable: LEFT TURN WITH CAUTION, WATCH FOR THROUGH TRAFFIC, or LEFT TURNS WATCH FOR ONCOMING TRAFFIC. Signs would again be placed at position A for left-turning motorists on approach 2 (see figure 51). For right turns, the message would be WATCH FOR TRAFFIC FROM LEFT and the sign would be mounted at the driver's eye level (position B), although the flasher-augmentation would be rather distracting. A new installation of a (continuous) flasher-augmented traffic control device would cost around $500.

While the relatively modest cost is an advantage for this countermeasure, flashing signs can quickly lose their effectiveness for local drivers and can be very obtrusive in a mixed land-use area.

Pavement Markings for a Safety Zone. The idea here is to present the driver with an additional cue about where any oncoming vehicle is in relation to a potential conflict area in the intersection. The implicit message is: if the oncoming vehicle is "in the paint," do not attempt the maneuver. This could be done most simply by using a solid color for a section of the roadway--say from the stop line to a point upstream 250 to 300 ft (76 to 91 m), i.e., the distance a vehicle travels in 6 s or so at 35 mi/h (56 km/h). This treatment is illustrated in figure 51--treatment is applied on approach 1, to assist a driver on approach 3. If the treatment is used for all left turn movements in an intersection, no further treatment would be necessary for the right turn maneuver. This could be accomplished using either colored asphalt or paint. The former would be more expensive, at an estimated cost of $3,000 per lane (at the time of repaving). The latter would cost only approximately $500 per lane, but paint might have an adverse effect on surface friction. Moreover, both schemes would lose all or some of their effectiveness under low lighting conditions and/or adverse weather conditions (e.g., with snow on the road).

Transverse striping could also be used to convey the message. Either uniformly-spaced or variably-spaced lines could be used. In the latter instance, the lines would be closer together nearer to the stop line to give the illusion of higher oncoming vehicle speed.

Perhaps the strongest argument against this alternative is the relatively vague message that is conveyed. The pavement marking can be confused (or interfere) with crosswalk markings and there is no absolutely correct interpretation. Moreover, it is not clear that it would help the target group of older drivers recognize fast-approaching cars as being a problem. In a worst-case scenario, the older driver learns to use the paint cue, but a speeding driver is not "in the paint" when the turning driver commences the maneuver and is involved in a conflict anyway.

Special Signal Phases for Permitted Turns. Over the years there has been a variety of alternatives to the straightforward use of red, yellow, and green signal phases. For example, green-yellow and red-yellow have been used to divide up the change interval, and flashing colors have been used in various situations--often associated with protected vs. permitted turns. In Michigan, for example, a flashing-red phase is sometimes used after a protected phase (green arrow) to indicate that a left turn is still permitted. Flashing yellow is similarly used in Washington State. The advantage of these special uses of the traditional color phases is to provide an enhanced message regarding which movements are allowed and which are not. A green ball after a green arrow--i.e., for the permissive phase--has been linked to increased demands on a driver for timely and accurate decision-making at intersections.[1]

The message of a flashing phase does not directly address performance deficits that an older driver may have, but it does serve to implicitly highlight that permissive turns are somehow different from protected turns and should introduce an additional cautionary note to the information being processed by the turning driver. Flashing red, for example, is already associated with flasher-augmented STOP signs. One drawback is that it is only effective when there is a separate signal head for the left-turn lane--it would not work, for example, in a simple intersection where there is only one head that controls all lanes or when the left turn maneuver shares a lane with some other option. Flashing green could also be used for the permitted turning maneuver and more readily adapted to shared lanes.

It should also be noted that this countermeasure lends itself to combination with both the eye-level signal alternative and supplementary advisory plates (e.g., LEFT TURN WITH CAUTION WHEN FLASHING). Unlike the other countermeasures, there is no parallel treatment for right turns (although a flashing red for a right-turn-only lane makes sense for right-turn-on-red).

The cost of implementing this countermeasure is largely dependent on the kind of signal in place in a given situation. If the signal controller is sophisticated, then the installation cost is minimal, but could go as high as $35,000 if all-new signal hardware is required.

Low-End Solutions

"Low-end" countermeasures are those that are inexpensive and simple to implement. They would include, for example, the use of warning signs and advisory plates, without use of flashers, to augment the message.

<u>Advisory/Warning Signs</u>. Several advisory messages were discussed in the context of the more active traffic control devices presented above. Several of these signs could also be used alone or in combination in more passive applications. These messages could be put in an overhead position (near the signal head) or diagonally across the intersection (e.g., in location A for turning drivers on approach 2 in figure 51) at eye level. Reasonable messages include: LEFT TURN WITH CAUTION, LEFT TURNS WATCH FOR THROUGH TRAFFIC, LEFT TURNS WATCH FOR ONCOMING TRAFFIC, LEFT TURN YIELD TO THROUGH TRAFFIC, and other variations. For right-turning drivers, messages (in position B on approach 2 in figure 51) include: WATCH FOR TRAFFIC FROM LEFT, RIGHT TURN YIELD TO TRAFFIC FROM LEFT, and RIGHT TURN WITH CAUTION, among others. Other combinations are also currently in use, such as, at selected sites in Michigan, LEFT TURNS YIELD ON GREEN BALL (where the words GREEN BALL are replaced, literally, with a green ball). The latter is mentioned with some reservation since research has identified this as a potentially confusing sign that is especially problematic for older drivers.[1]

Traffic control devices bearing such messages have the advantage of being useful (for the most part) at a range of intersection types--e.g., LEFT TURNS YIELD TO THROUGH TRAFFIC is equally applicable at a signalized intersection with an exclusive turning lane as it is for the uncontrolled leg of a two-way STOP-controlled intersection. In addition, such installations are the least expensive of any considered here--the average sign costs less than $200 for fabrication and installation.

The effectiveness of such simple devices is hard to estimate and, in all likelihood, depends on the context in which it is used. In a cluttered, urban environment these signs would probably have a reasonably high likelihood of being overlooked--especially if the intersection is complex or has a relatively high volume of use.

THROUGH DRIVERS

The other half of any turn-related accident is the vehicle with which the turning vehicle came into conflict. In many instances, the driver of this vehicle also shares in the fault associated with the accident and, as noted earlier in this research, the through drivers are often cited for violations such as speeding. It is logical then, to consider countermeasures that are directed toward affecting the behavior of these drivers as well. Unlike the turning driver, the options for dealing with this driver are more limited: conflicts are either eliminated by protecting turning maneuvers from the through driver or they are permitted. Prohibition of the through movement is a far less acceptable option and is not considered. IVHS-type solutions are, as above, not considered here.

High-End Solutions

Vehicle Presence-Activated Signs. Vehicle-activated signs to warn the through driver of potential conflicts with turning vehicles are somewhat more straightforward than the reverse situation discussed above. Mere detection of a vehicle presence in the left-turn lane is sufficient to result in a positive sign condition. For example, a vehicle presence activates an overhead or roadside sign that communicates one of the following messages: WATCH FOR LEFT-TURNING VEHICLE (when the opposing lane is an exclusive left-turn lane) or WATCH FOR POSSIBLE LEFT TURNS (for any opposing vehicle presence when there is no exclusive lane and the left turn is allowed). The sign has several variations: a blacked-out message sign that is lit only when potentially conflicting vehicles are present; a flasher-augmented sign (with the additional plate, WHEN FLASHING); and a visible sign (e.g., WATCH FOR POSSIBLE LEFT TURNS), which is internally lit and flashes when conflicts are possible. The last version has the advantage of always giving the message to the motorists (a better fail-safe mode). Unlike the vehicle-activated message for the turning driver, heavy traffic here would cause the sign to be continually lit, which presents no particular problem.

This countermeasure is illustrated in figure 52. Assuming that the through movement is on approach 1 and the conflict is with potential left turns from approach 3, the sensing devices would be in the lane nearest the centerline of approach 3 and upstream, while the sign would be at the roadside on approach 1 in position C (or possibly overhead). This countermeasure requires the installation of sensing devices, some sort of controller system, and the illuminated or flasher-augmented sign. The costs, as before, would be around $4,000 per approach that is implemented.

With reference to figure 52, a variation of this sign could also take care of the potential conflicts between the through vehicle on approach 1 and vehicles turning right, into its path from approach 2. A sensing device would need to be placed in the curb lane of approach 2 and the sign message at location C would have to be made more general--e.g., WATCH FOR TURNING VEHICLES and, depending on the type of sign used, possibly supplemented with WHEN FLASHING.

Vehicle Speed-Activated Signs. Rather than merely informing through drivers of a potential conflict with a turning vehicle, a more direct approach can be taken for vehicles that are traveling at a high speed. Sensors can be arrayed in a "speed trap" to calculate the speeds of the through drivers and inform them that their speed is too fast through the use of an overhead or roadside sign that flashes the message, SPEED TOO FAST FOR INTERSECTION (or a similar message). This message is different from those discussed above in that the message is positive and clear and should leave only limited liability for the municipality in the case of sign failure. The sign should be blacked-out when speeds are acceptable, although the WHEN FLASHING message could be used with a flasher-augmented sign. The deployment position would also be at position C or overhead. The overhead deployment could be lane specific. The costs should be about the same as the presence-activated sign in the last section.

Note that the sensor array used for this sign could also be used for warning the turning driver of the through vehicle--that is, the sensors could trigger both the sign warning the through driver to slow down as well as warning the turning driver that a high-speed driver is approaching.

Mid-Range Solutions

Flasher-Augmented Warning Devices. As for the turning driver, there are a variety of messages that might also be appropriate for providing a reminder to the through driver to watch out for potential conflicts. In this instance, the devices are augmented with continuously flashing beacons. These are all directed toward encouraging the through driver to double-check for conflicts. Sign messages would include WATCH FOR TURNING TRAFFIC and be placed either overhead or at the roadside (e.g., position C for approach 1 in figure 52). A standard intersection warning sign with a speed advisory plate and continuously flashing beacons could also be used. A new installation of a flasher-augmented traffic control device would cost around $500.

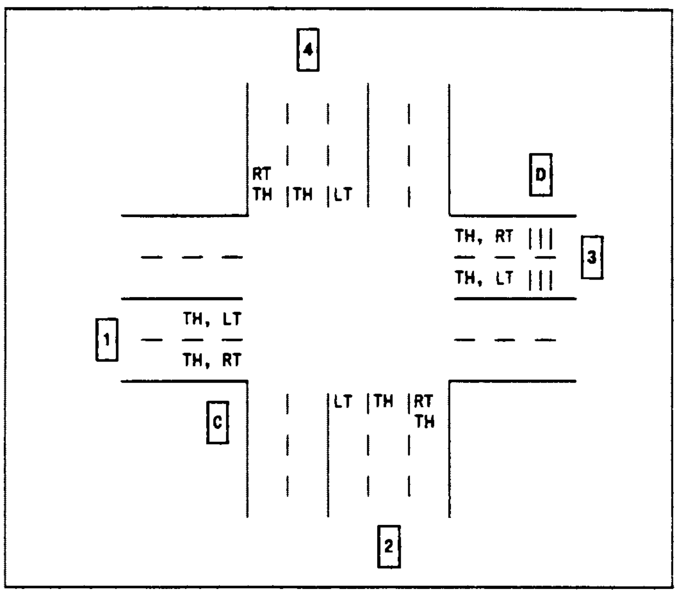


Figure 52. Typical intersection for countermeasure deployment for through vehicles. [Note that boxed numbers refer to the approach (e.g., approach 1) while the boxed letters are sign deployment locations referred to in the text.]

As mentioned earlier, the relatively modest cost is an advantage for this countermeasure. However, flashing signs can quickly lose their effectiveness for local drivers and can be very obtrusive in a mixed land-use area.

Speed-Sensitive Rumble Strips. Rumble strips have been used effectively in many instances to warn drivers of an upcoming situation (e.g., an isolated STOP sign in a rural area) or simply to alert drivers to the driving task in general (e.g., placement of rumble strips on the shoulder of the road to prevent "drift-off-the-road accidents" at night). In selected instances, they have also been tested as speed control devices (e.g., in a rural village in Maine) and are widely used at turnpike toll booths, both as an attention-getting device and for speed control. The countermeasure proposed here is for the design of strips that are relatively noisier at higher speeds--the strips would be placed so that the through driver would be warned to slow down for the intersection. Placement is shown in figure 52 on approach 3 (adjacent to position D). This countermeasure could also be supplemented with a simple warning/advisory sign with the message REDUCE SPEED FOR INTERSECTION.

The disadvantages of rumble strips include the noise and riding discomfort for the driver (possibly regardless of whether or not they need to slow down) and the noise transmitted to the roadside. (This latter issue was raised in the context of a speed-control experiment in the rural Maine village--sleeping residents were bothered by vehicles going over the strips at night.) In some instances, drivers have been noted to speed up over strips to reduce vibration (the ride can literally be smoother at higher speeds).

Costs for installation of rumble strips is relatively modest--about $250 for a set for one lane. Multiple lanes and/or multiple sets in a lane would increase the cost proportionately.

Transverse Stripping. Transverse stripping was offered as a countermeasure to aid the turning driver in judging the position and speed of the opposing through driver. The speed cue is also offered to the through driver by the same marking pattern, and may be more effective than for the turning driver. There have, however, been some experiments with special markings for speed reduction and they have generally provided inconclusive results--it would be especially problematic for the relatively small speed differentials observed at most urban/suburban intersections. The cost of stripping would probably be in the range of $200 to $300.

Low-End Solutions

There are a variety of low-end solutions that would have applicability in warning the through driver of the potential for conflicts with turning drivers or that the through driver should reduce speed. Costs are about the same for each and the relative effectiveness is reasonably well-known. Several are listed below:

- Advisory/warning signs warning of the actions of other motorists at the intersection. Appropriate messages would include: OPPOSING VEHICLES MAY TURN LEFT and WATCH FOR TURNING VEHICLES.

- Advanced warning signs that warn of the intersection itself. Signs and messages include: the "signal ahead" symbol sign, intersection symbol sign with an advisory speed plate, or a speed limit reduction in the vicinity of the intersection.

- Advisory/warning signs that warn through motorists to modify their own driving: SLOW FOR INTERSECTION or REDUCE SPEED.

While the cost of such options are low (on the order of $200 for a sign), the effectiveness of such treatments would not expected to be very high, especially for frequent motorists who tend to ignore such background passive signs. (The responsible agency is, however, offered some protection in the context of tort liability.)

DISCUSSION AND CONCLUSIONS

The basic contention underlying the countermeasure options that have been identified here is that an intersection accident is a function of either a turning driver's error, a through driver's error, or some combination of the two (regardless of who is cited for having caused the accident). In this context, the countermeasures presented above have had two different objectives: to enhance motorist knowledge of what is going on in an intersection during the turning maneuvers and to modify the motorist's actions in some manner. Moreover, the needs and actions of both the turning and through drivers have been addressed. An example of the former is advising the turning motorist of an oncoming vehicle that may be too close. An example of the latter is advising the through motorist to slow down because his/her speed is too high.

In terms of addressing the target group of older drivers, some of the treatments are directed specifically at ameliorating performance deficits that are more common among the group (i.e., a reminder to watch for through traffic) while others are more indirect (i.e., slowing down approaching traffic benefits older, turning drivers even if it doesn't result in any direct affect on their behavior). In any event, the countermeasures have not been explicitly field-tested for their impact on reducing intersection-related accidents involving the older driver. In that context, the countermeasures that have been discussed are suggestions for further research. In this context, some suggestions are presented below for testing the most promising ideas.

Engineering judgment by present project staff indicates the most promising ideas to be:

- Eye-level signals for the turning drivers.
- Speed-activated warnings for through drivers.
- Rumble strips for through drivers.
- Special signal phase treatments for permitted turns (e.g., flashing red or yellow) for turning drivers.
- Advisory/warning signs for turning and through drivers.

A systematic evaluation needs to be undertaken that addresses the effectiveness of different countermeasures under field conditions. Key elements in such evaluations are provided below.

The first two elements of the program address generic questions raised by the candidate countermeasures suggested above.

- Sign position. Several countermeasures included traffic control devices to be placed diagonally opposite the turning driver. This placement is different from what drivers normally encounter (although it is not unique). The efficacy of placing signs and signals at different heights in this position needs to be determined. This includes evaluating the placement itself as well as sign (signal) height. If this placement is not effective, then countermeasures that depend on the placement position should be discarded. Of special interest here is the eye-level placement--it is hypothesized that it is more effective to give the driver pertinent information in the same plane as the oncoming vehicles, thus reducing the time required to scan the relevant field.

In addition, the relative effectiveness of overhead vs. roadside placement of signs (with the same message) near intersections needs to be evaluated (e.g., is an advisory message, WATCH FOR TURNING TRAFFIC, most effective overhead near the signal head or at the roadside?).

- Supplementary signal heads. It is hypothesized that drivers may lose track of the signal phase (e.g., as they move up into the intersection, the overhead signal head cannot be seen) or it is simply too difficult and/or distracting to glance back and forth between the signal and the oncoming traffic. Thus, use of supplementary signal heads could offset that problem--again, the extra information is being provided at eye level, in the same plane as the traffic that is being monitored. The efficacy of providing these additional signal heads should be evaluated in three different positions: diagonally across the intersection; to the left-turning driver's left (e.g., on a median island); and to the right-turning driver's right.

In addition to testing the common elements, the devices themselves should be evaluated. Those that need special attention are:

- Rumble strips. It seems fairly clear that rumble strips are fairly effective in selected applications and especially when they are used as an attention-getting device (e.g., reducing run-off-the-road accidents). It is less clear if they would have the desired effect in intersection applications such as described above.

- Speed-activated devices. Speed-activated devices have a fairly long history of effective use in freeway and rural road environments--from overhead signs that flash when speed limits are exceeded to warnings regarding the appropriate speed for curves ahead. While this positive experience should translate to lower-speed, more urbanized situations, it remains to be demonstrated conclusively.

- Special signal phase treatments. There has been some laboratory testing of such treatments, but comparative field testing needs to be done (there is a study underway on the effectiveness of Michigan's use of flashing red).

- Special purpose advisory/warning signs. Finally, assuming that some or all of the higher-level treatments are effective, the question that remains is whether simpler and far less expensive treatments are substantially inferior.

CONCLUSIONS AND RECOMMENDATIONS

This research project confirmed that older drivers are overrepresented in certain accident types that in turn are described by specific traffic maneuver requirements. A number of other recent reports have shown that accident rates for older drivers are disproportionately high for specific maneuvers--in particular, turning maneuvers at intersections--and the present analysis is in agreement with such findings. In this project, a prediction of the relative difficulty of various traffic maneuvers and accident rates for older drivers was also made, based on hypothesized requirements for drivers' motion perception of other vehicles and the amount of angular expansion information available to serve as velocity/distance change cues over a given observation interval. These predictions were supported in the ordinal relationships among age-by-accident type cross-tabulations obtained in this project, interpreted using methods of induced exposure. The conclusion from this early work in the project was that age differences in motion perception capabilities represent a likely source of difficulty for specific traffic maneuver problems experienced by older drivers.

The empirical study of age differences in driver performance capabilities that are presumed to depend upon accurate motion perception include two sets of experiments in this project. In the first experiment, drivers in three age groups--18-55, 56-74, and 75+ years of age--estimated the time-to-collision of an approaching vehicle from both stationary and moving perspectives. The conflict vehicle approached at varying speeds and was removed from the view of the test subject at varying times/distances relative to the subject. In the second experiment, drivers with the intention of initiating a variety of traffic maneuvers evaluated the "last safe moment to proceed" in relation to a designated conflict vehicle to determine a gap judgment measure. Both the time-to-collision (TTC) and gap judgment measures were obtained under laboratory conditions using multiple stimulus presentation methodologies in a driving simulator. Limited controlled field validation data were also obtained for both types of dependent measures, using the same test sample viewing the same target (conflict) vehicle as in the laboratory simulations. The conclusions drawn from these efforts and resulting recommendations for accommodating the traffic maneuver difficulties of older drivers are summarized as follows.

In the TTC experiments, a result showing overestimation by older vs. younger test subjects would have provided a possible explanation of the overinvolvement of this group in incidents involving certain maneuvers--for example, left turns at intersections. This result was not found. Actually, the present data led to the conclusion that older drivers nearly universally **underestimate** TTC; this effect was more pronounced for the older rather than the younger drivers, and the magnitude of underestimation grew with higher vehicle approach speeds. It may be noted that other researchers have concluded that elderly subjects judge cars to be traveling more rapidly, relative to the judgment of younger subjects in controlled studies of velocity estimation.[32] Also, research has demonstrated the same effect for head-on vehicle approaches.[33] This type of perceptual error should, if anything, lead to more conservative driving decisions, and seems therefore not to be linked to documented older driver maneuver problems in any direct manner.

In the gap judgment experiments, many different maneuvers were investigated under laboratory conditions, but only two of the most safety-critical--left turns against traffic and right turns into traffic--were also studied in the field. As discussed in more detail below, the largest component of the data obtained in the laboratory driving simulator was in response to video images of driving scenes, which were later judged to be of questionable validity with respect to real-world performance. It may still be noted, however, that for a number of the maneuvers tested--passing on a two-lane highway, freeway merge, freeway exit/weave--there were no significant differences demonstrated in the simulator gap judgment data.

While again acknowledging limitations in the (high frequency) spatial information available to subjects viewing video stimulus scenes, it may tentatively be concluded that anecdotal reports of older driver difficulties in freeway entry/merge situations need not necessarily be attributed to motion perception problems. For a majority of interchange types, ramp geometry permits a longitudinal view of vehicles on the mainline for at least some time, which should allow more nearly veridical judgments of approach vehicle motion. In this situation, cognitive demands associated with the need to rapidly shift attention between left-rear (mainline) and forward (ramp) visual search areas, and/or head/neck flexibility requirements to redirect one's gaze in a timely fashion could disproportionately penalize older drivers. Among those who rely on mirror views of the mainline to judge freeway entry gaps, the significance of age differences in freeway entry decisions is unknown. In any event, no recommendations for countermeasures were justified by the present findings for this maneuver.

Interestingly, for the car following, maneuver subjects' responses using cinematic as well as video test images showed that the oldest drivers judged the minimum safe gap between themselves and a lead vehicle to be significantly **smaller** than did either the young/middle-age or young-old comparison groups. This outcome--which has yet to be validated in the field--supports the conclusion that older drivers may be at heightened risk in this situation, especially when deficits in reaction time (RT) for this group are taken into account.

The minimum safe gap judgment data for the left turn against traffic and right turn into traffic maneuvers deserve the greatest attention in this project. Under (controlled) field conditions, where a stationary observer waited at an intersection to turn left, the mean gaps accepted by the two older driver groups remained virtually unchanged as the target (conflict) vehicle approached at a higher vs. a lower speed. Meanwhile, the 18-55 age group judged the minimum safe gap to proceed with the turn to be 25 percent larger with a 60 mi/h (96 km/h) approach speed than with a 30 mi/h (48 km/h) approach speed. Similarly, when waiting at a stop sign to turn right ahead of traffic on a two-lane highway, the 18-55 age group required a gap 41 percent larger when the conflict vehicle approached at 60 vs. 30 mi/h (96 vs. 48 km/h). By contrast, the minimum safe gap sizes accepted by the 56-74 and 75+ age groups in the field differed by only 1 percent and 7 percent, respectively, for one target speed vs. another. These results supported the conclusion that older drivers suffer impairments in the ability to perceive velocity differences in the motion of (head-on) approach vehicles, reinforcing the findings of recent, related studies.[34] As discussed earlier, however, the extent to which gaps accepted by drivers were safe or unsafe in any absolute sense could not be validly determined, since this was not the objective of the experimental design and test protocols applied in the field study.

This relative insensitivity of older drivers to the speed of opposing vehicles in turning situations further suggested that this group relies primarily, if not exclusively, on instantaneous perceptions of vehicle separation distance to reach maneuver "go/no go" decisions. References cited in the background information chapter support this conclusion. Project recommendations for countermeasures to improve the safety of turning movements by older drivers were developed accordingly, as discussed below.

Two complementary countermeasure strategies were identified in this research as having the highest potential to ameliorate older driver problems in turning situations: (1) cue the older/turning driver to the presence of vehicles approaching at speeds that exceed the posted limit by a fixed amount; and (2) slow down through traffic and make these drivers more aware of the potential for a conflict ahead with a turning vehicle. Specific recommendations for promising options deserving further research include speed-activated warning devices, rumble strips for through traffic, and special permissive signal phase treatments that may induce greater caution among turning drivers (e.g., flashing yellow or flashing red). A lower-cost option--advisory/warning signs to alert all drivers to a heightened potential for conflict--also should be evaluated to determine its cost-effectiveness ratio in comparison to the more expensive approaches previously listed.

Finally, the contrast between the minimum safe gap judgments of a common test sample in the field and in response to three simulation display methodologies--large-screen video, television monitor (video), and large-screen 35mm cinematic--led to some preliminary conclusions regarding the appropriateness and validity of alternative technologies for image (driving scene) presentation. As one would expect, increasing conflict vehicle speed led to increasing minimum safe gap judgments for turning movements under controlled field conditions for young/middle-age drivers, i.e., those individuals defining baseline motion perception performance levels in this research. The mean response levels for this group were flat when the identical stimuli were shown using a video source, however. For the older groups, whose response levels were relatively constant across varying conflict vehicle approach speeds in the field, minimum safe gap judgments for turning maneuvers when video stimulus scenes were presented actually **declined** as target speed increased from 30 to 60 mi/h (48 to 96 km/h).

The patterns of gap judgment responses by age group and conflict vehicle approach speed using 35mm cinematic stimulus presentation paralleled those obtained under field conditions for these maneuvers. Apparently, this technique was the most valid, and deserves recommendation as the most valid, feasible option for measuring driver perceptual-cognitive response to realistic driving scenes.

More general recommendations pertaining to the parameters of image quality for successful (part-task) driving simulation also emerged from these findings. Key stimulus dimensions highlighted by the present results are image accommodation distance, image resolution (high spatial frequency information), image size, and image perspective (movement in depth).

With the television monitor data collection methodology, image viewing distance was only 18 in (46 cm). Such an unrealistic visual accommodation distance in a simulator provides subtle but powerful cues to a driver. Until shown otherwise, it seems prudent to assume that an accommodation distance shortened to this range will lead to instant discrimination of an image as a video source, eliciting responses that reflect the risk acceptance behaviors of a game, rather than those that influence real-world driving decisions. Obtaining realistic size and perspective cues is also not feasible using a television monitor to display simulated driving scenes, though it should be noted that relationships between camera lens focal length, image magnification, and subject viewing distance in the simulator determine correct perspective, not the display medium per se.

Accommodation distance was beyond 6.5 ft (2 m) for the large-screen data collection methodologies, but response patterns discussed above led to the conclusion that the NTSC video source was deficient, even when a digital scan converter was applied to enhance image quality. The high spatial frequency information (used by the younger subjects in maneuver decisions) was absent in the videodisc-based test conditions, and younger subjects' gap judgments across varying target speeds were conspicuously even. Subjects' gap judgments with the cinematic display suggest that it was not only quantitatively different from the video images--the equivalent of over 3,000 horizontal lines of visual information vs. under 400 lines for the NTSC video signal--but it also provided a scene texture resulting in **qualitatively** different response patterns.

To retain the considerable benefits of videodisc storage and playback of test scenes for driving simulation, research into the applications of high-definition television (HDTV) is recommended. As digital editing capabilities evolve and system costs fall, it may become common to record real-world scenarios with startling realism, then to alter a sign, signal, or other feature of interest in the highway environment and systematically evaluate the effect on drivers with diverse characteristics and capabilities with an unprecedented degree of experimental control. Ultimately, the ability to capture valid perceptual and cognitive responses from drivers under high demand conditions, without risk, must be held up as the criterion by which simulation methodologies are judged.

APPENDIX A. CROSS-TABULATION TABLES FOR SPECIFIED DRIVER AGES, HIGHWAY, AND MANEUVER TYPES FOR THE MICHIGAN ACCIDENT ANALYSIS

Table 6. Cross-tabulation of driver 1 age by driver 2 age: merging and weaving on limited-access highways.

driver 1 age	driver 2 age				
	≤26	27-55	56-75	76-98	totals
≤26	155 (24.1)[1]	418 (65.1)	63 (9.8)	6 (0.9)	642 (38.2)
27-55	216 (25.5)	519 (61.2)	110 (13.0)	3 (0.4)	848 (50.4)
56-75	43 (26.1)	103 (62.4)	16 (9.7)	3 (1.8)	165 (9.8)
76-98	4 (14.8)	20 (74.1)	3 (11.1)	0 (0.0)	27 (1.6)
totals	418 (24.9)	1060 (63.0)	192 (11.4)	12 (0.7)	1682

[1]cell entries: number of accidents (row percentage)

Table 7. Cross-tabulation of driver 1 age by violation: merging and weaving on limited-access highways.

driver 1 age	violation[1]				
	speeding	failure to yield	lane usage	following	other
≤26	102 (14.8)[2]	52 (7.5)	152 (22.1)	358 (52.0)	25 (3.6)
27-55	128 (14.3)	96 (10.8)	217 (24.3)	429 (48.0)	23 (2.5)
56-75	21 (12.1)	33 (19.0)	54 (31.0)	60 (34.5)	6 (3.5)
76-98	2 (7.4)	8 (29.6)	9 (33.3)	7 (25.9)	1 (3.7)
totals	253 (14.2)	189 (10.6)	432 (24.2)	854 (47.9)	55 (3.1)

[1]violations: speeding, failure to yield right of way, improper lane usage, following too closely
[2]number of accidents (row percentage)

Table 8. Cross-tabulation of driver 1 age by driver 2 age: lane change on limited-access highways.

driver 1 age	driver 2 age				
	≤26	27-55	56-75	76-98	totals
≤26	232 (28.5)[1]	501 (61.5)	79 (9.7)	3 (0.4)	815 (32.5)
27-55	380 (27.1)	872 (62.2)	139 (9.9)	11 (0.8)	1402 (55.9)
56-75	65 (24.3)	177 (66.3)	24 (9.0)	1 (0.4)	267 (10.7)
76-98	5 (22.7)	16 (72.7)	1 (4.5)	0 (0.0)	22 (0.9)
totals	682 (27.2)	1566 (62.5)	243 (9.7)	15 (0.6)	2506

[1]cell entries: number of accidents (row percentage)

Table 9. Cross-tabulation of driver 1 age by violation: lane change on limited-access highways.

driver 1 age	driver 1 violation[1]				
	speeding	failure to yield	lane usage	following	other
≤26	995 (23.5)[2]	84 (2.0)	797 (18.9)	2131 (50.4)	219 (5.2)
27-55	1036 (18.2)	133 (2.3)	1494 (26.3)	2622 (46.1)	406 (7.1)
56-75	146 (17.0)	36 (4.2)	282 (32.8)	342 (39.7)	55 (6.4)
76-98	17 (20.0)	1 (2.3)	36 (42.4)	28 (32.9)	3 (3.5)
totals	2194 (24.9)	254 (2.3)	2609 (24.0)	5213 (47.2)	593 (5.5)

[1]violations: speeding, failure to yield right of way, improper lane usage, following too closely
[2]number of accidents (row percentage)

Table 10. Cross-tabulation of driver 1 age by driver 2 age:
left turns against traffic
(driver 1 turning left, driver 2 going straight).

driver 1 age	driver 2 age				
	≤26	27-55	56-75	76-98	totals
≤26	1752 (39.5)[1]	2251 (50.8)	393 (8.9)	39 (0.9)	4435 (41.4)
27-55	1521 (39.5)	1958 (50.8)	350 (9.1)	26 (0.8)	3855 (36.0)
56-75	663 (38.2)	855 (49.2)	205 (11.8)	14 (0.8)	1737 (16.2)
76-98	249 (36.6)	347 (51.0)	75 (11.0)	10 (1.5)	681 (6.4)
totals	4185 (39.1)	5411 (50.5)	1023 (9.6)	89 (0.8)	10708

[1]cell entries: number of accidents (row percentage)

Table 11. Cross-tabulation of driver 1 age by driver 2 age:
left turns against traffic
(driver 1 going straight, driver 2 turning left).

driver 1 age	driver 2 age				
	≤26	27-55	56-75	76-98	totals
≤26	359 (38.7)[1]	464 (50.1)	86 (9.3)	18 (1.9)	927 (49.8)
27-55	271 (36.6)	372 (50.2)	89 (50.2)	9 (1.2)	741 (39.8)
56-75	54 (32.1)	84 (50.0)	25 (14.9)	5 (3.0)	168 (9.0)
76-98	9 (33.3)	11 (40.7)	6 (22.2)	1 (3.7)	27 (1.4)
totals	693 (37.2)	931 (50.5)	206 (11.1)	33 (1.8)	1863

[1]cell entries: number of accidents (row percentage)

Table 12. Cross-tabulation of driver 1 age by driver 2 age:
crossing traffic/gap acceptance
(angle-straight accidents at nonsignalized locations).

driver 1 age	driver 2 age				
	≤26	27-55	56-75	76-98	totals
≤26	986 (33.8)[1]	1542 (52.8)	354 (12.1)	36 (1.2)	2918 (41.6)
27-55	794 (31.6)	1343 (53.5)	334 (13.3)	41 (1.6)	2512 (35.8)
56-75	355 (32.3)	586 (53.3)	132 (12.0)	26 (2.4)	1099 (15.7)
76-98	165 (34.0)	239 (49.2)	77 (15.8)	5 (1.0)	486 (6.9)
totals	2300 (32.8)	3710 (52.9)	897 (12.8)	108 (1.5)	7015

[1]cell entries: number of accidents (row percentage)

Table 13. Mean (X) and standard deviation (s.d.) estimated vs. actual time-to-collision (s) and target recognition distance (ft) by age group and target speed, for stationary observers viewing a head-on target approach using a video projection stimulus presentation.

a. ESTIMATED TTC

Driver Age Group	Actual TTC = 2.5 s									Actual TTC = 5.0 s									Actual TTC = 7.5 s								
	Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)	14	.56	.47	21	.68	.75	22	1.13	1.37	23	1.35	1.36	22	2.37	2.05	22	3.14	3.11	24	2.47	2.11	25	3.77	4.25	25	5.01	4.42
Young-old (56-74)	10	.44	.79	12	.29	.20	17	.45	.32	19	.68	.57	22	.96	.61	25	1.43	.87	22	1.20	1.03	26	1.48	.88	26	4.25	5.51
Old-old (75+)	*	*	*	*	*	*	8	.92	1.28	*	*	*	12	.73	.60	18	1.11	1.47	12	.70	.74	17	1.73	2.25	21	2.85	4.33

b. RECOGNITION DISTANCE (ft)

Driver Age Group	Actual TTC = 2.5 s									Actual TTC = 5.0 s									Actual TTC = 7.5 s								
	Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)	14	635	185	21	494	178	22	393	158	23	459	159	22	279	157	20	182	137	24	352	151	23	193	122	10	115	105
Young-old (56-74)	10	563	207	12	529	135	17	428	172	19	516	168	22	321	168	21	237	118	22	420	177	23	246	149	13	118	95
Old-old (75+)	*	*	*	*	*	*	7	331	209	*	*	*	12	286	155	14	211	148	11	393	166	11	210	118	9	93	74

*less than 5 subjects completed responses in this cell

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

Table 14. Mean (X) and standard deviation (s.d.) estimated vs. actual time-to-collision (s) and target recognition distance (ft) by age group and target speed, for stationary observers viewing a head-on target approach using a television monitor stimulus presentation.

a. ESTIMATED TTC

Driver Age Group	Actual TTC = 2.5 s									Actual TTC = 5.0 s									Actual TTC = 7.5 s								
	Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)	22	1.13	.71				22	2.05	1.52	22	2.39	.92				22	4.97	3.49	22	4.47	2.34				22	7.27	4.78
Young-old (56-74)	26	.71	.36				26	1.32	.62	26	1.84	1.00				26	3.31	1.38	26	3.29	1.35				25	4.25	1.86
Old-old (75+)	21	.63	.67				20	2.46	3.84	20	.87	.76				21	2.92	4.02	21	1.83	1.49				19	5.11	5.28

b. RECOGNITION DISTANCE (ft)

Driver Age Group	Actual TTC = 2.5 s									Actual TTC = 5.0 s									Actual TTC = 7.5 s								
	Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)	22	533	133				22	349	113	22	414	133				21	182	105	22	312	129				8	55	31
Young-old (56-74)	26	572	191				26	365	165	26	486	173				24	205	139	26	356	175				17	82	68
Old-old (75+)	21	547	140				18	344	178	20	423	164				17	215	173	21	313	192				7	157	58

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

Table 15. Mean (X) and standard deviation (s.d.) estimated vs. actual time-to-collision (s) and target recognition distance (ft) by age group and target speed, for stationary observers viewing a head-on target approach using a cinematic projection stimulus presentation.

a. ESTIMATED TTC

Driver Age Group	Actual TTC = 2.5 s									Actual TTC = 5.0 s									Actual TTC = 7.5 s								
	Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)	19	.56	.36				21	.69	.46	22	1.65	.98				23	2.52	1.30	23	2.64	1.65				23	5.15	2.93
Young-old (56-74)	18	.30	.23				19	.49	.28	23	1.19	.57				25	2.31	1.10	25	2.25	.92				25	4.18	1.66
Old-old (75+)	12	.50	.59				16	1.34	3.51	18	.91	1.04				20	1.57	1.36	19	1.40	1.38				20	2.04	1.76

b. RECOGNITION DISTANCE (ft)

Driver Age Group	Actual TTC = 2.5 s									Actual TTC = 5.0 s									Actual TTC = 7.5 s								
	Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)	19	889	160				21	879	101	22	853	169				23	888	75	23	856	186				22	894	60
Young-old (56-74)	18	742	176				18	874	83	23	774	188				25	844	95	25	776	173				19	863	64
Old-old (75+)	12	747	189				15	749	136	18	696	155				19	804	119	18	710	169				20	852	86

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

Table 16. Mean (X) and standard deviation (s.d.) estimated vs. actual time-to-collision (s) by age group and target speed, for <u>stationary</u> observers viewing a <u>head-on</u> target approach in the <u>controlled field</u> trials.

Driver Age Group	Actual TTC = 2.5 s									Actual TTC = 5.0 s									Actual TTC = 7.5 s								
	Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)										13	2.17	1.41				14	3.14	1.72	13	3.65	1.80				13	3.91	2.69
Young-old (56-74)										19	1.91	1.06				19	2.81	1.44	20	2.76	1.29				20	4.83	1.91
Old-old (75+)										16	2.46	2.10				16	2.82	2.20	16	2.52	1.92				16	3.61	2.38

1 mi/h = 1.61 km/h

Table 17. Mean (X) and standard deviation (s.d.) estimated vs. actual time-to-collision (s) and target recognition distance (ft) by age group and target speed, for stationary observers viewing an intersecting target approach (90°) using a video projection stimulus presentation.

a. ESTIMATED TTC

Driver Age Group	Actual TTC = 2.5 s									Actual TTC = 5.0 s									Actual TTC = 7.5 s								
	Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)	18	.85	1.24	20	.86	.99	23	1.21	1.42	25	1.81	1.44	24	2.27	2.23	25	3.42	3.25	24	3.03	2.07	24	4.12	4.12	25	6.36	4.32
Young-old (56-74)	11	.35	.21	13	.37	.35	20	.51	.39	24	1.26	1.52	25	1.09	.88	27	2.16	2.11	25	1.40	.77	27	2.09	1.34	27	4.75	3.76
Old-old (75+)	*	*	*	*	*	*	9	.42	.36	5	3.32	6.39	7	.64	.82	17	.80	.95	10	1.87	3.41	14	.89	1.07	21	3.56	4.10

b. RECOGNITION DISTANCE (ft)

Driver Age Group	Actual TTC = 2.5 s									Actual TTC = 5.0 s									Actual TTC = 7.5 s								
	Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)	18	552	154	20	486	174	23	339	155	25	440	158	24	294	133	23	144	112	24	350	161	19	150	133	6	119	162
Young-old (56-74)	11	580	142	13	423	105	20	303	145	24	465	181	25	295	128	22	202	121	25	359	178	25	177	166	6	126	127
Old-old (75+)	*	*	*	*	*	*	9	386	198	5	490	166	7	338	193	15	177	170	9	300	197	10	193	160	6	95	73

*less than 5 subjects completed responses in this cell

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

Table 18. Mean (X) and standard deviation (s.d.) estimated vs. actual time-to-collision (s) and target recognition distance (ft) by age group and target speed, for stationary observers viewing an intersecting target approach (90°) using a television monitor stimulus presentation.

a. ESTIMATED TTC

Driver Age Group	Actual TTC = 2.5 s									Actual TTC = 5.0 s									Actual TTC = 7.5 s								
	Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)	22	1.28	.82				22	1.66	1.38	22	3.04	2.08				22	4.50	3.32	22	4.05	2.29				22	7.06	4.04
Young-old (56-74)	26	.84	.27				26	.97	.47	26	1.82	.83				26	2.54	.72	26	2.33	.97				24	5.16	3.31
Old-old (75+)	20	1.98	5.49				21	.75	.47	20	.94	.78				21	1.74	1.28	21	1.24	1.06				19	5.36	4.50

b. RECOGNITION DISTANCE (ft)

Driver Age Group	Actual TTC = 2.5 s									Actual TTC = 5.0 s									Actual TTC = 7.5 s								
	Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)	22	617	156				22	379	125	22	531	173				21	185	119	22	362	151				14	95	80
Young-old (56-74)	26	651	199				26	397	94	26	526	184				25	218	135	26	356	186				13	100	121
Old-old (75+)	20	574	239				21	392	112	20	481	253				20	193	133	21	419	234				9	89	64

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

Table 19. Mean (X) and standard deviation (s.d.) estimated vs. actual time-to-collision (s) and target recognition distance (ft) by age group and target speed, for stationary observers viewing an intersecting target approach (90°) using a cinematic projection stimulus presentation.

a. ESTIMATED TTC

Driver Age Group	Actual TTC = 2.5 s									Actual TTC = 5.0 s									Actual TTC = 7.5 s								
	Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)	21	.56	.56				20	.82	.59	22	1.98	1.29				23	2.44	1.63	23	3.25	2.41				23	4.90	2.99
Young-old (56-74)	14	.31	.19				22	.39	.26	23	1.27	.53				24	1.72	.68	25	2.40	.88				25	3.72	1.48
Old-old (75+)	14	1.49	3.91				14	.56	.58	19	.67	.53				21	1.45	1.04	19	1.48	1.61				21	2.28	1.56

b. RECOGNITION DISTANCE (ft)

Driver Age Group	Actual TTC = 2.5 s									Actual TTC = 5.0 s									Actual TTC = 7.5 s								
	Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)	21	920	124				20	950	96	22	941	73				23	941	92	23	944	89				23	961	87
Young-old (56-74)	14	914	92				22	900	86	23	890	102				24	884	89	25	891	108				24	903	86
Old-old (75+)	14	797	109				14	775	139	19	821	98				20	861	98	19	793	138				17	897	73

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

Table 20. Mean (X) and standard deviation (s.d.) estimated vs. actual time-to-collision (s) and target recognition distance (ft) by age group and target speed, for moving observers viewing a head-on target approach using a video projection stimulus presentation.

a. ESTIMATED TTC

Driver Age Group	Actual TTC = 2.5 s									Actual TTC = 5.0 s									Actual TTC = 7.5 s								
	Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)	22	1.68	3.74	22	1.36	1.07	22	2.28	4.03	25	2.08	1.70	25	2.89	2.31	25	2.55	1.82	25	3.33	2.30	25	3.98	3.80	24	4.21	3.14
Young-old (56-74)	12	.52	.61	24	1.46	3.00	24	.74	.62	23	1.03	.66	26	2.65	4.37	26	1.72	1.54	28	2.06	2.50	27	2.40	3.05	26	2.48	2.76
Old-old (75+)	9	1.35	2.21	11	.77	.49	15	1.23	1.38	15	2.23	5.77	18	.94	.90	19	1.51	2.00	15	1.40	1.92	17	2.94	4.05	22	1.65	1.96

b. RECOGNITION DISTANCE (ft)

Driver Age Group	Actual TTC = 2.5 s									Actual TTC = 5.0 s									Actual TTC = 7.5 s								
	Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)	22	559	213	22	500	177	20	436	195	25	419	227	24	333	213	19	240	158	22	352	211	20	219	146	14	84	61
Young-old (56-74)	12	472	327	24	454	242	23	352	208	22	386	258	23	407	172	20	259	132	21	433	127	20	259	130	16	129	95
Old-old (75+)	7	589	360	8	411	174	14	450	216	11	526	310	11	367	197	8	227	114	9	360	241	12	276	149	9	106	83

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

Table 21. Mean (X) and standard deviation (s.d.) estimated vs. actual time-to-collision (s) and target recognition distance (ft) by age group and target speed, for moving observers viewing a head-on target approach using a television monitor stimulus presentation.

a. ESTIMATED TTC

Driver Age Group	Actual TTC = 2.5 s									Actual TTC = 5.0 s									Actual TTC = 7.5 s								
	Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)	22	1.58	.96				22	2.43	1.24	22	3.17	1.89				22	4.04	2.25	22	4.95	2.67				22	6.05	4.02
Young-old (56-74)	26	1.03	.53				26	2.24	1.65	26	2.10	1.00				26	2.99	1.22	25	2.98	1.50				25	4.03	2.03
Old-old (75+)	20	1.22	1.67				21	2.07	2.52	21	1.67	1.28				19	3.37	3.95	20	2.45	1.56				19	4.43	4.48

b. RECOGNITION DISTANCE (ft)

Driver Age Group	Actual TTC = 2.5 s									Actual TTC = 5.0 s									Actual TTC = 7.5 s								
	Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)	22	620	159				22	415	234	22	518	155				20	259	153	22	367	165				17	116	84
Young-old (56-74)	26	592	210				24	450	185	26	477	200				23	282	160	23	365	199				14	125	69
Old-old (75+)	20	473	218				18	352	224	21	358	219				11	263	201	19	264	225				8	144	101

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

Table 22. Mean (X) and standard deviation (s.d.) estimated vs. actual time-to-collision (s) and target recognition distance (ft) by age group and target speed, for moving observers viewing a head-on target approach using a cinematic projection stimulus presentation.

a. ESTIMATED TTC

Driver Age Group	Actual TTC = 2.5 s									Actual TTC = 5.0 s									Actual TTC = 7.5 s								
	Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)	21	.81	.52				22	1.25	.82	23	2.49	1.60				23	3.01	1.75	22	3.14	2.17				21	5.02	2.54
Young-old (56-74)	21	.36	.30				24	.77	.46	25	1.22	.60				25	2.57	1.03	23	2.34	1.28				24	3.94	1.27
Old-old (75+)	14	.42	.42				19	.94	.65	19	1.11	.70				18	1.99	1.24	18	1.41	1.02				19	2.93	1.90

b. RECOGNITION DISTANCE (ft)

Driver Age Group	Actual TTC = 2.5 s									Actual TTC = 5.0 s									Actual TTC = 7.5 s								
	Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)	21	932	150				22	970	90	23	967	108				23	938	124	22	937	175				20	996	104
Young-old (56-74)	21	915	183				24	904	178	25	905	195				25	854	172	23	881	205				19	944	99
Old-old (75+)	14	786	201				19	756	182	18	860	150				16	753	143	18	829	189				12	880	76

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

APPENDIX C. SAS GLM OUTPUT (F-TABLES) FOR MOTION JUDGMENT EXPERIMENTS

(refer to pages 71 through 75 in the text)

(GRP = group, TS = target speed, TD = target approach direction, SN(GRP) = subjects within group error term)

ESTIMATED TTC: Stationary Observer

Actual TTC = 2.5 s **Stimulus Presentation = Video Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	3775678	1887839	0.72	0.4916
TS	2	6215344	3107672	10.41	0.0001
GRP*TS	4	9309066	2327266	7.79	0.0001
TD	1	651343	651343	2.18	0.1418
GRP*TD	2	3159685	1579842	5.29	0.0060
TS*TD	2	1020561	510280	1.71	0.1845
GRP*TS*TD	3	2293027	764342	2.56	0.0572
ERROR	151	45086651	298587		
SN(GRP)	61	160272807	2627423		

ESTIMATED TTC: Stationary Observer

Actual TTC = 2.5 s **Stimulus Presentation = TV Monitor**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	21126604	10563302	1.61	0.2070
TS	1	17886936	17886936	6.16	0.0139
GRP*TS	2	915112	457556	0.16	0.8544
TD	1	3004264	3004264	1.03	0.3105
GRP*TD	2	1210825	605412	0.21	0.8121
TS*TD	1	37058577	37058577	12.75	0.0004
GRP*TS*TD	2	30325788	15162894	5.22	0.0062
ERROR	196	569516420	2905696		
SN(GRP)	66	432202782	6548527		

ESTIMATED TTC: Stationary Observer

Actual TTC = 2.5 s **Stimulus Presentation = Cinematic Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	3470204	1735102	0.66	0.5226
TS	1	687562	687562	0.37	0.5438
GRP*TS	2	393457	196728	0.11	0.8995
TD	1	153999	153999	0.08	0.7738
GRP*TD	2	234763	117382	0.06	0.9387
TS*TD	1	6730952	6730952	3.63	0.0590
GRP*TS*TD	2	11780238	5890119	3.17	0.0450
ERROR	136	252446882	1856227		
SN(GRP)	62	164066766	2646238		

ESTIMATED TTC: Stationary Observer

Actual TTC = 5.0 s **Stimulus Presentation = Video Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	92537479	46268740	4.21	0.0187
TS	2	34913609	17456805	10.07	0.0001
GRP*TS	4	21000111	5250028	3.03	0.0182
TD	1	10374955	10374955	5.99	0.0151
GRP*TD	2	1316250	658125	0.38	0.6844
TS*TD	2	8484714	424357	2.45	0.0885
GRP*TS*TD	4	5794822	1448705	0.84	0.5034
ERROR	256	443634542	1732947		
SN(GRP)	71	780011922	10986083		

ESTIMATED TTC: Stationary Observer

Actual TTC = 5.0 s **Stimulus Presentation = TV Monitor**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	196330827	98165414	10.25	0.0001
TS	1	155151849	155151849	67.71	0.0001
GRP*TS	2	10240135	5120068	2.23	0.1098
TD	1	5628050	5628050	2.46	0.1187
GRP*TD	2	4936479	2468239	1.08	0.3426
TS*TD	1	18238487	18238487	7.96	0.0053
GRP*TS*TD	2	764700	382350	0.17	0.8464
ERROR	196	449144656	2291554		
SN(GRP)	66	632049357	9576505		

ESTIMATED TTC: Stationary Observer

Actual TTC = 5.0 s **Stimulus Presentation = Cinematic Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	41054032	20527016	6.40	0.0029
TS	1	38240802	38240802	95.18	0.0001
GRP*TS	2	20207	10104	0.03	0.9752
TD	1	447435	447435	1.11	0.2927
GRP*TD	2	1438699	719349	1.79	0.1698
TS*TD	1	1369016	1369016	3.41	0.0665
GRP*TS*TD	2	2389588	1194794	2.97	0.0536
ERROR	185	74325473	401759		
SN(GRP)	66	211615602	3206297		

ESTIMATED TTC: Stationary Observer

Actual TTC = 5.0 s **Stimulus Presentation = Field Trials**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	2245059	1122529	0.24	0.7871
TS	1	11856521	11856521	11.83	0.0013
GRP*TS	2	1500282	750141	0.75	0.4790
ERROR	45	45115170	1002559		
SN(GRP)	46	214560956	4664369		

ESTIMATED TTC: Stationary Observer

Actual TTC = 7.5 s **Stimulus Presentation = Video Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	319790600	159895300	5.57	0.0057
TS	2	536591110	268295555	39.78	0.0001
GRP*TS	4	15107559	3776890	0.56	0.6919
TD	1	25643241	25643240	3.80	0.0521
GRP*TD	2	1705328	852664	0.13	0.8813
TS*TD	2	9569783	4784891	0.71	0.4927
GRP*TS*TD	4	11146808	2786702	0.41	0.7991
ERROR	306	2063885168	6744722		
SN(GRP)	71	2037828364	28701808		

ESTIMATED TTC: Stationary Observer

Actual TTC = 7.5 s **Stimulus Presentation = TV Monitor**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	270742816	135371408	6.00	0.0040
TS	1	524679587	524679587	111.20	0.0001
GRP*TS	2	30758868	15379434	3.26	0.0406
TD	1	1978840	1978840	0.42	0.5180
GRP*TD	2	1087442	543721	0.12	0.8912
TS*TD	1	15452138	15452138	3.27	0.0719
GRP*TS*TD	2	8480565	4240282	0.90	0.4088
ERROR	191	901206497	4718359		
SN(GRP)	66	1489798334	22572702		

ESTIMATED TTC: Stationary Observer

Actual TTC = 7.5 s **Stimulus Presentation = Cinematic Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	217153074	108576537	9.95	0.0002
TS	1	150856823	150856823	143.49	0.0001
GRP*TS	2	17150397	8575198	8.16	0.0004
TD	1	198116	198116	0.19	0.6647
GRP*TD	2	1599672	799836	0.76	0.4687
TS*TD	1	2539358	2539358	2.42	0.1218
GRP*TS*TD	2	3827291	1913645	1.82	0.1648
ERROR	193	202909820	1051346		
SN(GRP)	66	719989693	10908935		

ESTIMATED TTC: Stationary Observer

Actual TTC = 7.5 s **Stimulus Presentation = Field Trials**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	13612191	6806095	0.98	0.3821
TS	1	28976769	28976769	30.37	0.0001
GRP*TS	2	13407909	6703955	7.03	0.0022
ERROR	45	42935841	954130		
SN(GRP)	47	325724461	6930308		

RECOGNITION DISTANCE: Stationary Observer

Actual TTC = 2.5 s **Stimulus Presentation = Video Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	11269	5634	0.08	0.9275
TS	2	514836	257418	26.77	0.0001
GRP*TS	4	67903	16976	1.77	0.1387
TD	1	28544	28544	2.97	0.0870
GRP*TD	2	16444	8222	0.86	0.4273
TS*TD	2	19586	9793	1.02	0.3636
GRP*TS*TD	3	83255	27752	2.89	0.0376
ERROR	151	1452025	9616		
SN(GRP)	60	4483193	74720		

RECOGNITION DISTANCE: Stationary Observer

Actual TTC = 2.5 s **Stimulus Presentation = TV Monitor**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	59968	29984	0.44	0.6489
TS	1	2956650	2956650	284.74	0.0001
GRP*TS	2	18573	9286	0.89	0.4106
TD	1	158485	158485	15.26	0.0001
GRP*TD	2	6610	3305	0.32	0.7278
TS*TD	1	10234	10234	0.99	0.3221
GRP*TS*TD	2	21531	10766	1.04	0.3566
ERROR	194	2014435	10384		
SN(GRP)	66	4546101	68880		

RECOGNITION DISTANCE: Stationary Observer

Actual TTC = 2.5 s **Stimulus Presentation = Cinematic Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	524539	262270	9.48	0.0003
TS	1	34779	34779	3.32	0.0705
GRP*TS	2	12286	6143	0.59	0.5573
TD	1	280500	280500	26.81	0.0001
GRP*TD	2	45760	22880	2.19	0.1163
TS*TD	1	8038	8038	0.77	0.3823
GRP*TS*TD	2	59906	29953	2.86	0.0606
ERROR	134	1402022	10463		
SN(GRP)	62	1715567	27670		

RECOGNITION DISTANCE: Stationary Observer

Actual TTC = 5.0 s **Stimulus Presentation = Video Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	120367	60184	0.83	0.4405
TS	2	2648239	1324120	172.48	0.0001
GRP*TS	4	10940	2735	0.36	0.8395
TD	1	26134	26134	3.40	0.0663
GRP*TD	2	19155	9577	1.25	0.2891
TS*TD	2	29675	14837	1.93	0.1470
GRP*TS*TD	4	32678	8170	1.06	0.3749
ERROR	238	1827090	7677		
SN(GRP)	70	5078774	72554		

RECOGNITION DISTANCE: Stationary Observer

Actual TTC = 5.0 s **Stimulus Presentation = TV Monitor**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	58020	29010	0.42	0.6597
TS	1	5261048	5261048	501.01	0.0001
GRP*TS	2	23708	11854	1.13	0.3256
TD	1	99696	99696	9.49	0.0024
GRP*TD	2	18451	9226	0.88	0.4171
TS*TD	1	74610	74610	7.11	0.0084
GRP*TS*TD	2	22614	11307	1.08	0.3428
ERROR	186	1953161	10501		
SN(GRP)	66	4573222	69291		

RECOGNITION DISTANCE: Stationary Observer

Actual TTC = 5.0 s **Stimulus Presentation = Cinematic Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	501716	250858	8.29	0.0006
TS	1	130330	130330	16.40	0.0001
GRP*TS	2	39635	19817	2.49	0.0854
TD	1	442643	442643	55.69	0.0001
GRP*TD	2	7249	3624	0.46	0.6345
TS*TD	1	76589	76589	9.64	0.0022
GRP*TS*TD	2	11198	5599	0.70	0.4957
ERROR	183	1454503	7948		
SN(GRP)	66	1997664	30268		

RECOGNITION DISTANCE: Stationary Observer

Actual TTC = 7.5 s **Stimulus Presentation = Video Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	18114	9057	0.16	0.8492
TS	2	2756233	1378116	131.84	0.0001
GRP*TS	4	26761	6690	0.64	0.6346
TD	1	90117	90117	8.62	0.0037
GRP*TD	2	32682	16341	1.56	0.2122
TS*TD	2	4427	2214	0.21	0.8093
GRP*TS*TD	4	23104	5776	0.55	0.6974
ERROR	189	1975650	10453		
SN(GRP)	69	3813594	55269		

RECOGNITION DISTANCE: Stationary Observer

Actual TTC = 7.5 s **Stimulus Presentation = TV Monitor**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	23160	11580	0.26	0.7739
TS	1	4097356	4097356	307.30	0.0001
GRP*TS	2	33102	16551	1.24	0.2925
TD	1	32000	32000	2.40	0.1238
GRP*TD	2	32159	16079	1.21	0.3028
TS*TD	1	22485	22485	1.69	0.1964
GRP*TS*TD	2	51161	25580	1.92	0.1510
ERROR	128	1706696	13334		
SN(GRP)	66	2969885	44998		

RECOGNITION DISTANCE: Stationary Observer

Actual TTC = 7.5 s **Stimulus Presentation = Cinematic Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	426808	213404	8.18	0.0007
TS	1	161010	161010	16.53	0.0001
GRP*TS	2	49162	24581	2.52	0.0831
TD	1	343426	343426	35.25	0.0001
GRP*TD	2	9139	4569	0.47	0.6264
TS*TD	1	36549	36549	3.75	0.0543
GRP*TS*TD	2	9365	4682	0.48	0.6192
ERROR	180	1753698	9743		
SN(GRP)	66	1720906	26074		

ESTIMATED TTC: Moving Observer

Actual TTC = 2.5 s **Stimulus Presentation = Video Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	17908451	8954225	1.14	0.3276
TS	2	3987448	1993724	0.39	0.6758
GRP*TS	4	18187521	4546880	0.90	0.4689
ERROR	88	445659114	5064308		
SN(GRP)	64	504627455	7884804		

ESTIMATED TTC: Moving Observer

Actual TTC = 2.5 s **Stimulus Presentation = TV Monitor**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	4225896	2112948	0.74	0.4798
TS	1	33003265	33003265	17.82	0.0001
GRP*TS	2	932703	466351	0.25	0.7781
ERROR	65	120364542	1851762		
SN(GRP)	66	187810266	2845610		

ESTIMATED TTC: Moving Observer

Actual TTC = 2.5 s **Stimulus Presentation = Cinematic Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	4263224	2131612	5.52	0.0061
TS	1	6441627	6441627	27.84	0.0001
GRP*TS	2	49081	24540	0.11	0.8996
ERROR	50	11567275	231346		
SN(GRP)	65	25095874	386090		

ESTIMATED TTC: Moving Observer

Actual TTC = 5.0 s **Stimulus Presentation = Video Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	32052380	16026190	1.84	0.1666
TS	2	3782571	1891285	0.30	0.7383
GRP*TS	4	34666061	8666515	1.39	0.2401
ERROR	122	758658998	6218516		
SN(GRP)	71	618971014	8717902		

ESTIMATED TTC: Moving Observer

Actual TTC = 5.0 s **Stimulus Presentation = TV Monitor**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	35663047	17831524	2.98	0.0575
TS	1	40747788	40747788	15.85	0.0002
GRP*TS	2	3177608	1588804	0.62	0.5421
ERROR	64	164504109	2570377		
SN(GRP)	66	394390288	5975610		

ESTIMATED TTC: Moving Observer

Actual TTC = 5.0 s **Stimulus Presentation = Cinematic Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	32420552	16210276	6.67	0.0023
TS	1	30114268	30114268	52.52	0.0001
GRP*TS	2	4168294	2084147	3.63	0.0322
ERROR	62	35552966	573435		
SN(GRP)	65	158075199	2431926		

ESTIMATED TTC: Moving Observer

Actual TTC = 7.5 s **Stimulus Presentation = Video Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	144043887	72021944	6.25	0.0031
TS	2	19763709	9881854	1.46	0.2353
GRP*TS	4	11147645	2786911	0.41	0.7992
ERROR	127	857593611	6752706		
SN(GRP)	73	841831059	11531932		

ESTIMATED TTC: Moving Observer

Actual TTC = 7.5 s **Stimulus Presentation = TV Monitor**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	119380767	59690384	5.04	0.0092
TS	1	73756201	73756201	16.64	0.0001
GRP*TS	2	7689460	3844730	0.87	0.4253
ERROR	61	270460317	4433776		
SN(GRP)	66	781824232	11845822		

ESTIMATED TTC: Moving Observer

Actual TTC = 7.5 s **Stimulus Presentation = Cinematic Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	60181590	30090795	6.40	0.0029
TS	1	84121982	84121982	59.15	0.0001
GRP*TS	2	1279214	639607	0.45	0.6401
ERROR	56	79647612	1422279		
SN(GRP)	65	305544641	4700687		

RECOGNITION DISTANCE: Moving Observer

Actual TTC = 2.5 s **Stimulus Presentation = Video Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	69616	34808	0.47	0.6268
TS	2	661358	330679	9.48	0.0002
GRP*TS	4	184243	46061	1.32	0.2696
ERROR	81	2826780	34899		
SN(GRP)	62	4585391	73958		

RECOGNITION DISTANCE: Moving Observer

Actual TTC = 2.5 s **Stimulus Presentation = TV Monitor**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	305588	152794	2.43	0.0955
TS	1	908614	908614	45.83	0.0001
GRP*TS	2	21974	10987	0.55	0.5775
ERROR	60	1189562	19826		
SN(GRP)	66	4142112	62759		

RECOGNITION DISTANCE: Moving Observer

Actual TTC = 2.5 s **Stimulus Presentation = Cinematic Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	556017	278008	8.10	0.0007
TS	1	4078	4078	0.22	0.6383
GRP*TS	2	42152	21076	1.16	0.3231
ERROR	50	911850	18237		
SN(GRP)	65	2231336	34328		

RECOGNITION DISTANCE: Moving Observer

Actual TTC = 5.0 s **Stimulus Presentation = Video Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	574	287	0.00	0.9958
TS	2	1126203	563102	23.26	0.0001
GRP*TS	4	227488	56872	2.35	0.0602
ERROR	90	2179070	24212		
SN(GRP)	64	4357817	68091		

RECOGNITION DISTANCE: Moving Observer

Actual TTC = 5.0 s **Stimulus Presentation = TV Monitor**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	121810	60905	1.21	0.3055
TS	1	1197314	1197314	97.58	0.0001
GRP*TS	2	72790	36395	2.97	0.0604
ERROR	51	625759	12270		
SN(GRP)	66	3329062	50440		

RECOGNITION DISTANCE: Moving Observer

Actual TTC = 5.0 s **Stimulus Presentation = Cinematic Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	442976	221488	5.80	0.0048
TS	1	154148	154148	21.68	0.0001
GRP*TS	2	54311	27156	3.82	0.0276
ERROR	59	419482	7110		
SN(GRP)	65	2482829	38197		

RECOGNITION DISTANCE: Moving Observer

Actual TTC = 7.5 s **Stimulus Presentation = Video Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	125035	62518	2.19	0.1213
TS	2	1103369	551685	33.60	0.0001
GRP*TS	4	74720	18680	1.14	0.3454
ERROR	74	1214876	16417		
SN(GRP)	60	1716075	28601		

RECOGNITION DISTANCE: Moving Observer

Actual TTC = 7.5 s **Stimulus Presentation = TV Monitor**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	38263	19132	0.54	0.5845
TS	1	1501910	1501910	135.66	0.0001
GRP*TS	2	57052	28526	2.58	0.0908
ERROR	34	376414	11071		
SN(GRP)	63	2225712	35329		

RECOGNITION DISTANCE: Moving Observer

Actual TTC = 7.5 s **Stimulus Presentation = Cinematic Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	257896	128948	3.60	0.0329
TS	1	1242	1242	0.15	0.6980
GRP*TS	2	14865	7432	0.91	0.4089
ERROR	45	366591	8146		
SN(GRP)	63	2253681	35773		

APPENDIX D. TABLES OF DESCRIPTIVE STATISTICS SUMMARIZING RESULTS OF GAP ACCEPTANCE STUDY

Table 23. Mean (X) and standard deviation (s.d.) target recognition distance (ft) and judged minimum safe gap (ft) to perform a left turn maneuver at an intersection by a stationary observer, for varying subject age groups and target speeds, using a video projection stimulus presentation.

a. TARGET RECOGNITION DISTANCE (ft)

Driver Age Group	Target Speed 20 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)	25	962	171	25	971	150	25	870	155	25	814	182
Young-old (56-74)	28	998	199	28	975	187	28	872	199	28	855	224
Old-old (75+)	23	1004	129	24	999	142	23	925	135	23	850	184

b. JUDGED MINIMUM SAFE GAP TO PERFORM MANEUVER (ft)

Driver Age Group	Target Speed 20 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)	25	460	208	25	480	182	25	512	163	25	487	152
Young-old (56-74)	28	756	249	28	748	220	28	656	251	28	630	223
Old-old (75+)	24	889	196	24	830	156	23	759	169	24	728	189

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

Table 24. Mean (X) and standard deviation (s.d.) target recognition distance (ft) and judged minimum safe gap (ft) to perform a two-lane highway crossing maneuver at an intersection by a stationary observer, for varying subject age groups and target speed, using video projection stimulus presentation.

a. TARGET RECOGNITION DISTANCE (ft)

Driver Age Group	Target Speed 20 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)	25	1374	321	25	1427	288	25	1360	276	25	1345	270
Young-old (56-74)	28	1327	366	28	1358	357	27	1293	335	28	1281	343
Old-old (75+)	23	1354	361	24	1356	336	20	1168	342	23	1215	311

b. JUDGED MINIMUM SAFE GAP TO PERFORM MANEUVER (ft)

Driver Age Group	Target Speed 20 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)	25	360	138	25	396	129	25	435	121	25	477	126
Young-old (56-74)	28	627	350	28	586	298	27	627	294	28	643	301
Old-old (75+)	23	894	418	24	842	423	23	836	374	23	727	316

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

Table 25. Mean (X) and standard deviation (s.d.) target recognition distance (ft) and judged minimum safe gap (ft) to perform a right turn ahead of traffic maneuver at an intersection by a stationary observer, for varying subject age groups and target speeds, using video projection stimulus presentation.

a. TARGET RECOGNITION DISTANCE (ft)

Driver Age Group	Target Speed 20 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)	25	938	231	25	868	234	25	849	196	25	697	243
Young-old (56-74)	28	936	215	28	900	251	28	858	218	27	759	204
Old-old (75+)	23	958	204	24	915	215	24	850	202	24	678	178

b. JUDGED MINIMUM SAFE GAP TO PERFORM MANEUVER (ft)

Driver Age Group	Target Speed 20 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)	25	494	199	25	528	188	25	542	160	25	373	146
Young-old (56-74)	28	728	242	28	657	225	28	653	236	27	539	191
Old-old (75+)	24	749	257	24	697	194	24	665	200	24	494	196

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

Table 26. Mean (X) and standard deviation (s.d.) target recognition distance (ft) and judged minimum safe gap (ft) to perform a freeway merge maneuver from a ramp gore by a stationary observer, for varying age groups, using video projection stimulus presentation.

a. TARGET RECOGNITION DISTANCE (ft)

Driver Age Group	Target Speed 60 mi/h		
	n	X	s.d.
Young/middle-age (18-55)	25	681	134
Young-old (56-74)	28	740	127
Old-old (75+)	22	692	127

b. JUDGED MINIMUM SAFE GAP TO PERFORM MANEUVER (ft)

Driver Age Group	Target Speed 60 mi/h		
	n	X	s.d.
Young/middle-age (18-55)	25	419	127
Young-old (56-74)	28	503	181
Old-old (75+)	24	522	158

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

Table 27. Mean (X) and standard deviation (s.d.) distance (ft) of the judged minimum safe gap to perform a freeway exit/weave maneuver ahead of a car entering from a ramp by a moving observer, using video projection stimulus presentation.

Driver Age Group	Target Speed 30 mi/h		
	n	X	s.d.
Young/middle-age (18-55)	24	210	35
Young-old (56-74)	28	213	65
Old-old (75+)	22	221	59

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

Table 28. Mean (X) and standard deviation (s.d.) distance (ft) of the judged minimum safe gap to perform a car following maneuver on a two-lane highway by a moving observer, using video projection stimulus presentation.

Driver Age Group	Target Speed 45 to 60 mi/h		
	n	X	s.d.
Young/middle-age (18-55)	25	101	18
Young-old (56-74)	28	115	36
Old-old (75+)	23	88	40

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

Table 29. Mean (X) and standard deviation (s.d.) distance (ft) of the judged minimum safe gap to perform a car overtaking maneuver on a two-lane highway by a moving observer, using video projection stimulus presentation.

Driver Age Group	Target Speed 45 mi/h		
	n	X	s.d.
Young/middle-age (18-55)	25	92	22
Young-old (56-74)	28	102	35
Old-old (75+)	24	109	34

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

Table 30. Mean (X) and standard deviation (s.d.) target (oncoming vehicle) recognition distance (ft) and judged minimum safe gap (ft) to perform a passing maneuver on a two-lane highway by a moving observer, using video projection stimulus presentation.

a. TARGET RECOGNITION DISTANCE (ft)

Driver Age Group	Target Speed 45 mi/h		
	n	X	s.d.
Young/middle-age (18-55)	18	2344	561
Young-old (56-74)	16	2156	680
Old-old (75+)	12	2098	711

b. JUDGED MINIMUM SAFE GAP TO PERFORM MANEUVER (ft)

Driver Age Group	Target Speed 45 mi/h		
	n	X	s.d.
Young/middle-age (18-55)	23	1980	568
Young-old (56-74)	23	2062	689
Old-old (75+)	19	1933	726

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

Table 31. Mean (X) and standard deviation (s.d.) target recognition distance (ft) and judged minimum safe gap (ft) to perform a left turn maneuver at an intersection by a stationary observer, for varying subject age groups and target speeds, using television monitor stimulus presentation.

a. TARGET RECOGNITION DISTANCE (ft)

Driver Age Group	Target Speed 20 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)				22	864	138				22	750	154
Young-old (56-74)				26	890	166				26	762	163
Old-old (75+)				21	872	111				21	713	186

b. JUDGED MINIMUM SAFE GAP TO PERFORM MANEUVER (ft)

Driver Age Group	Target Speed 20 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)				22	312	112				22	327	95
Young-old (56-74)				26	451	184				26	406	139
Old-old (75+)				21	448	182				21	389	130

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

Table 32. Mean (X) and standard deviation (s.d.) target recognition distance (ft) and judged minimum safe gap (ft) to perform a two-lane highway crossing maneuver at an intersection by a stationary observer for varying subject age groups and target speeds, using television monitor stimulus presentation.

a. TARGET RECOGNITION DISTANCE (ft)

Driver Age Group	Target Speed 20 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)				22	1433	223				22	1318	284
Young-old (56-74)				26	1441	251				26	1291	268
Old-old (75+)				20	1414	140				20	1270	252

b. JUDGED MINIMUM SAFE GAP TO PERFORM MANEUVER (ft)

Driver Age Group	Target Speed 20 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)				22	348	140				22	425	145
Young-old (56-74)				26	521	254				26	542	212
Old-old (75+)				20	631	271				20	552	190

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

Table 33. Mean (X) and standard deviation (s.d.) target recognition distance (ft) and judged minimum safe gap (ft) to perform a right turn ahead of traffic maneuver at an intersection by a stationary observer, for varying subject age groups and target speeds, using television monitor stimulus presentation.

a. TARGET RECOGNITION DISTANCE (ft)

Driver Age Group	Target Speed 20 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)				22	954	193				22	770	230
Young-old (56-74)				25	932	196				26	762	195
Old-old (75+)				20	1022	192				20	763	140

b. JUDGED MINIMUM SAFE GAP TO PERFORM MANEUVER (ft)

Driver Age Group	Target Speed 20 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)				22	424	172				22	298	112
Young-old (56-74)				26	528	172				26	381	148
Old-old (75+)				20	573	202				20	384	162

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

Table 34. Mean (X) and standard deviation (s.d.) target recognition distance (ft) and judged minimum safe gap (ft) to perform a freeway merge maneuver from a ramp gore by a stationary observer, for varying age groups, using television monitor stimulus presentation.

a. TARGET RECOGNITION DISTANCE (ft)

Driver Age Group	Target Speed 60 mi/h		
	n	X	s.d.
Young/middle-age (18-55)	22	766	68
Young-old (56-74)	26	749	118
Old-old (75+)	19	737	130

b. JUDGED MINIMUM SAFE GAP TO PERFORM MANEUVER (ft)

Driver Age Group	Target Speed 60 mi/h		
	n	X	s.d.
Young/middle-age (18-55)	22	475	112
Young-old (56-74)	26	462	168
Old-old (75+)	19	445	144

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

Table 35. Mean (X) and standard deviation (s.d.) distance (ft) of the judged minimum safe gap to perform a car following maneuver on a two-lane highway by a moving observer, using television monitor stimulus presentation.

Driver Age Group	Target Speed 45 to 60 mi/h		
	n	X	s.d.
Young/middle-age (18-55)	22	81	17
Young-old (56-74)	26	76	26
Old-old (75+)	20	72	19

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

Table 36. Mean (X) and standard deviation (s.d.) distance (ft) of the judged minimum safe gap to perform a car overtaking maneuver on a two-lane highway by a moving observer, using television monitor stimulus presentation.

Driver Age Group	Target Speed 45 mi/h		
	n	X	s.d.
Young/middle-age (18-55)	22	69	20
Young-old (56-74)	26	69	24
Old-old (75+)	21	69	25

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

Table 37. Mean (X) and standard deviation (s.d.) target (oncoming vehicle) recognition distance (ft) and judged minimum safe gap (ft) to perform a passing maneuver on a two-lane highway by a moving observer, using television monitor stimulus presentation.

a. TARGET RECOGNITION DISTANCE (ft)

Driver Age Group	Target Speed 45 mi/h		
	n	X	s.d.
Young/middle-age (18-55)	21	1781	286
Young-old (56-74)	22	1944	435
Old-old (75+)	11	1729	403

b. JUDGED MINIMUM SAFE GAP TO PERFORM MANEUVER (ft)

Driver Age Group	Target Speed 45 mi/h		
	n	X	s.d.
Young/middle-age (18-55)	22	1376	448
Young-old (56-74)	25	1512	530
Old-old (75+)	17	1526	633

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

Table 38. Mean (X) and standard deviation (s.d.) target recognition distance (ft) and judged minimum safe gap (ft) to perform a left turn maneuver at an intersection by a stationary observer, for varying subject age groups and target speeds, using cinematic stimulus presentation.

a. TARGET RECOGNITION DISTANCE (ft)

Driver Age Group	Target Speed 20 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)				23	1109	57				23	1120	91
Young-old (56-74)				25	1050	120				24	1101	67
Old-old (75+)				20	1018	105				21	1046	92

b. JUDGED MINIMUM SAFE GAP TO PERFORM MANEUVER (ft)

Driver Age Group	Target Speed 20 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)				23	536	169				23	661	165
Young-old (56-74)				25	666	221				25	753	184
Old-old (75+)				21	708	235				21	750	202

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

Table 39. Mean (X) and standard deviation (s.d.) target recognition distance (ft) and judged minimum safe gap (ft) to perform a two-lane highway crossing maneuver at an intersection by a stationary observer, for varying subject age groups and target speed, using cinematic stimulus presentation.

a. TARGET RECOGNITION DISTANCE (ft)

Driver Age Group	Target Speed 20 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)				23	1510	58				23	1497	120
Young-old (56-74)				25	1459	149				23	1411	159
Old-old (75+)				21	1341	256				21	1344	247

b. JUDGED MINIMUM SAFE GAP TO PERFORM MANEUVER (ft)

Driver Age Group	Target Speed 20 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)				23	550	150				23	655	174
Young-old (56-74)				25	741	286				24	776	235
Old-old (75+)				21	824	323				21	868	309

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

Table 40. Mean (X) and standard deviation (s.d.) target recognition distance (ft) and judged minimum safe gap (ft) to perform a right turn ahead of traffic maneuver at an intersection by a stationary observer, for varying subject age groups and target speeds, using cinematic stimulus presentation.

a. TARGET RECOGNITION DISTANCE (ft)

Driver Age Group	Target Speed 20 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)				23	1204	86				23	1166	87
Young-old (56-74)				24	1149	104				25	1146	84
Old-old (75+)				21	1037	241				21	1062	155

b. JUDGED MINIMUM SAFE GAP TO PERFORM MANEUVER (ft)

Driver Age Group	Target Speed 20 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)				23	684	183				23	746	153
Young-old (56-74)				25	742	255				25	838	199
Old-old (75+)				21	663	251				21	752	192

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

Table 41. Mean (X) and standard deviation (s.d.) target recognition distance (ft) and judged minimum safe gap (ft) to perform a freeway merge maneuver from a ramp gore by a stationary observer, for varying age groups, using cinematic stimulus presentation.

a. TARGET RECOGNITION DISTANCE (ft)

Driver Age Group	Target Speed 60 mi/h		
	n	X	s.d.
Young/middle-age (18-55)	21	723	82
Young-old (56-74)	25	758	68
Old-old (75+)	22	801	34

b. JUDGED MINIMUM SAFE GAP TO PERFORM MANEUVER (ft)

Driver Age Group	Target Speed 60 mi/h		
	n	X	s.d.
Young/middle-age (18-55)	21	593	107
Young-old (56-74)	25	611	108
Old-old (75+)	22	613	97

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

Table 42. Mean (X) and standard deviation (s.d.) distance (ft) of the judged minimum safe gap to perform a car following maneuver on a two-lane highway by a moving observer, using cinematic stimulus presentation.

Driver Age Group	Target Speed 45 to 60 mi/h		
	n	X	s.d.
Young/middle-age (18-55)	23	93	18
Young-old (56-74)	25	96	26
Old-old (75+)	22	74	28

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

Table 43. Mean (X) and standard deviation (s.d.) distance (ft) of the judged minimum safe gap (ft) to perform a car overtaking maneuver on a two-lane highway by a moving observer, using cinematic stimulus presentation.

Driver Age Group	Target Speed 45 mi/h		
	n	X	s.d.
Young/middle-age (18-55)	23	83	24
Young-old (56-74)	25	99	34
Old-old (75+)	21	96	32

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

Table 44. Mean (X) and standard deviation (s.d.) target (oncoming vehicle) recognition distance (ft) and judged minimum safe gap (ft) to perform a passing maneuver on a two-lane highway by a moving observer, using cinematic stimulus presentation.

a. TARGET RECOGNITION DISTANCE (ft)

Driver Age Group	Target Speed 45 mi/h		
	n	X	s.d.
Young/middle-age (18-55)	22	2168	397
Young-old (56-74)	18	2142	496
Old-old (75+)	16	2316	523

b. JUDGED MINIMUM SAFE GAP TO PERFORM MANEUVER (ft)

Driver Age Group	Target Speed 45 mi/h		
	n	X	s.d.
Young/middle-age (18-55)	23	1668	406
Young-old (56-74)	23	1850	488
Old-old (75+)	19	1938	557

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

Table 45. Mean (X) and standard deviation (s.d.) distance (ft) of the judged minimum safe gap to perform a left turn maneuver at an intersection by a stationary observer, for varying subject age groups and target speeds, in controlled field trials.

Driver Age Group	Target Speed 20 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)				12	327	162				7	433	171
Young-old (56-74)				13	512	164				11	519	108
Old-old (75+)				14	546	203				15	527	173

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

Table 46. Mean (X) and standard deviation (s.d.) distance (ft) of the judged minimum safe gap to perform a right turn ahead of traffic maneuver at an intersection by a stationary observer, for varying subject age groups and target speeds, in controlled field trials.

Driver Age Group	Target Speed 20 mi/h			Target Speed 30 mi/h			Target Speed 45 mi/h			Target Speed 60 mi/h		
	n	X	s.d.	n	X	s.d.	n	X	s.d.	n	X	s.d.
Young/middle-age (18-55)				11	406	164				10	576	167
Young-old (56-74)				15	641	215				15	643	188
Old-old (75+)				15	605	233				11	568	185

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

APPENDIX E. SAS GLM OUTPUT (F-TABLES) FOR GAP ACCEPTANCE EXPERIMENTS

(refer to pages 86 and 99 through 101 in the text)

(GRP = group, TS = target speed, TD = target approach direction, SN(GRP) = subjects within group error term)

MINIMUM SAFE GAP

TD = Left Turn Against Traffic **DT1 = Video Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	5064114	2532057	20.66	0.0001
TS	3	374226	124742	9.57	0.0001
GRP*TS	6	386629	64438	4.95	0.0001
ERROR	221	2879449	13029		
SN(GRP)	74	9070324	122572		

MINIMUM SAFE GAP

TD = Left Turn Against Traffic **DT2 = TV Monitor**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	330373	165186	4.48	0.0149
TS	1	30208	30208	5.63	0.0206
GRP*TS	2	33682	16841	3.14	0.0499
ERROR	66	354248	5367		
SN(GRP)	66	2431506	36841		

MINIMUM SAFE GAP

TD = Left Turn Against Traffic **DT3 = Cinematic Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	448933	224467	3.21	0.0468
TS	1	246072	246072	31.55	0.0001
GRP*TS	2	38151	19076	2.45	0.0945
ERROR	66	514722	7799		
SN(GRP)	66	4618088	69971		

MINIMUM SAFE GAP

TD = Left Turn Against Traffic **DT4 = Field Trials**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	161748	80874	1.99	0.1498
TS	1	89224	89224	14.28	0.0009
GRP*TS	2	56106	28053	4.49	0.0220
ERROR	24	149920	6247		
SN(GRP)	42	1709272	40697		

MINIMUM SAFE GAP

TD = Highway Crossing **DT1 = Video Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	8082190	4041095	13.82	0.0001
TS	3	27072	9024	.55	0.6496
GRP*TS	6	402344	67057	4.08	0.0007
ERROR	218	3586041	16450		
SN(GRP)	74	21637903	292404		

MINIMUM SAFE GAP

TD = Highway Crossing **DT2 = TV Monitor**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	955180	477590	5.97	0.0042
TS	1	1379	1379	0.19	0.6646
GRP*TS	2	129282	64640	8.89	0.0004
ERROR	65	472619	7271		
SN(GRP)	65	5199705	79995		

MINIMUM SAFE GAP

TD = Highway Crossing **DT3 = Cinematic Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	1364488	682244	6.14	0.0036
TS	1	139550	139550	8.54	0.0048
GRP*TS	2	28180	14090	0.86	0.4269
ERROR	65	1061797	16335		
SN(GRP)	66	7331051	111077		

MINIMUM SAFE GAP

TD = Right Turn in Front of Traffic **DT1 = Video Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	1748140	874070	6.17	0.0033
TS	3	1746147	582049	62.82	0.0001
GRP*TS	6	194096	32349	3.49	0.0026
ERROR	221	2047617	9265		
SN(GRP)	74	10478367	141599		

MINIMUM SAFE GAP

TD = Right Turn in Front of Traffic **DT2= TV Monitor**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	334173	167087	3.53	0.0350
TS	1	799032	799032	139.94	0.0001
GRP*TS	2	21376	10688	1.87	0.1620
ERROR	65	371125	5709		
SN(GRP)	65	3076785	47335		

MINIMUM SAFE GAP

TD = Right Turn in Front of Traffic **DT3 = Cinematic Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	197700	98850	1.27	0.2870
TS	1	231778	231778	24.47	0.0001
GRP*TS	2	7415	3708	0.39	0.6777
ERROR	66	625201	9473		
SN(GRP)	66	5128756	77708		

MINIMUM SAFE GAP

TD = Right Turn in Front of Traffic **DT4 = Field Trials**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	242590	121295	2.14	0.1298
TS	1	33149	33149	3.32	0.0795
GRP*TS	2	51915	25957	2.60	0.0927
ERROR	27	269452	9980		
SN(GRP)	44	2494198	56686		

MINIMUM SAFE GAP

85 TD = Freeway Exit/Weave **DT1 = Video Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	1341	670	0.22	0.8022
SN(GRP)	71	215312	3032		

MINIMUM SAFE GAP

86 TD = Car Following **DT1 = Video Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	8837	4418	4.11	0.0203
SN(GRP)	73	78449	1075		

MINIMUM SAFE GAP

86 TD = Car Following **DT2 = TV Monitor**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	834	417	0.91	0.4063
SN(GRP)	65	29700	457		

MINIMUM SAFE GAP

86 TD = Car Following **DT3 = Cinematic Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	6154	3077	5.32	0.0072
SN(GRP)	66	38160	578		

MINIMUM SAFE GAP

87 TD = Overtaking Lead Vehicle **DT1 = Video Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	3408	1704	1.79	0.1745
SN(GRP)	74	70541	953		

MINIMUM SAFE GAP

87 TD = Overtaking Lead Vehicle DT2 = TV Monitor

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	2.836	1.418	0.00	0.9974
SN(GRP)	66	35282	534		

MINIMUM SAFE GAP

87 TD = Overtaking Lead Vehicle DT3 = Cinematic Projection

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	3611	1806	1.97	0.1470
SN(GRP)	66	60374	915		

MINIMUM SAFE GAP

88 TD = Passing DT1 = Video Projection

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	179846	89923	0.21	0.8142
SN(GRP)	62	27035017	436049		

MINIMUM SAFE GAP

88 TD = Passing **DT2 = TV Monitor**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	289113	144556	0.51	0.6046
SN(GRP)	61	17380780	284931		

MINIMUM SAFE GAP

88 TD = Passing **DT3 = Cinematic Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	809111	404555	1.74	0.1847
SN(GRP)	62	14447978	233032		

MINIMUM SAFE GAP

89 TD = Entering Freeway **DT1 = Video Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	149772	74886	3.01	0.0554
SN(GRP)	74	1841566	24886		

MINIMUM SAFE GAP

89 TD = Entering Freeway **DT2 = TV Monitor**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	9593	4796	0.23	0.7957
SN(GRP)	64	1338685	20917		

MINIMUM SAFE GAP

89 TD = Entering Freeway **DT3 = Cinematic Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	5216	2608	0.24	0.7864
SN(GRP)	65	702840	10813		

TARGET RECOGNITION DISTANCE

TD = Left Turn Against Traffic **DT1 = Video Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	71340	35670	0.36	0.6971
TS	3	1239853	413284	51.51	0.0001
GRP*TS	6	30413	5069	0.63	0.7047
ERROR	219	1757056	8023		
SN(GRP)	74	7280718	98388		

TARGET RECOGNITION DISTANCE

TD = Left Turn Against Traffic **DT2 = TV Monitor**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	26794	13397	0.34	0.7150
TS	1	615018	615018	71.83	0.0001
GRP*TS	2	11362	5681	0.66	0.5184
ERROR	66	565079	8562		
SN(GRP)	66	2622620	39737		

TARGET RECOGNITION DISTANCE

TD = Left Turn Against Traffic **DT3 = Cinematic Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	138767	69383	6.04	0.0039
TS	1	26784	26784	5.25	0.0252
GRP*TS	2	9290	4645	0.91	0.4075
ERROR	64	326498	5101		
SN(GRP)	66	758399	11491		

TARGET RECOGNITION DISTANCE

TD = Highway Crossing **DT1 = Video Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	514909	257455	0.72	0.4919
TS	3	512283	170761	8.29	0.0001
GRP*TS	6	88416	14736	0.72	0.6374
ERROR	215	4427438	20593		
SN(GRP)	74	26594047	359379		

TARGET RECOGNITION DISTANCE

TD = Highway Crossing **DT2 = TV Monitor**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	24593	12296	0.11	0.8920
TS	1	623347	623347	57.22	0.0001
GRP*TS	2	7863	3931	0.36	0.6984
ERROR	65	708108	10894		
SN(GRP)	65	6982585	107424		

TARGET RECOGNITION DISTANCE

TD = Highway Crossing **DT3 = Cinematic Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	571332	285666	5.26	0.0076
TS	1	11440	11440	1.69	0.1984
GRP*TS	2	13641	6821	1.01	0.3711
ERROR	64	433594	6775		
SN(GRP)	66	3582986	54288		

TARGET RECOGNITION DISTANCE

TD = Right Turn in Front of Traffic **DT1 = Video Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	30241	15121	0.10	0.9070
TS	3	2363058	787686	71.23	0.0001
GRP*TS	6	92557	15426	1.39	0.2177
ERROR	220	2432823	11058		
SN(GRP)	74	11451608	154751		

TARGET RECOGNITION DISTANCE

TD = Right Turn in Front of Traffic **DT2 = TV Monitor**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	47322	23661	0.37	0.6944
TS	1	1385257	1385257	120.53	0.0001
GRP*TS	2	48751	24375	2.12	0.1283
ERROR	64	735531	11493		
SN(GRP)	65	4192533	64501		

TARGET RECOGNITION DISTANCE

TD = Right Turn in Front of Traffic **DT3 = Cinematic Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	425977	212988	7.68	0.0010
TS	1	838	838	0.10	0.7556
GRP*TS	2	22487	11244	1.31	0.2763
ERROR	65	557028	8570		
SN(GRP)	66	1830358	27733		

TARGET RECOGNITION DISTANCE

85 TD = Freeway Exit/Weave **DT1 = Video Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	1	1176	1176	0.23	0.7175
SN(GRP)	1	5202	5202		

TARGET RECOGNITION DISTANCE

88 TD = Passing **DT1 = Video Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	518701	259350	0.62	0.5404
SN(GRP)	43	17861165	415376		

TARGET RECOGNITION DISTANCE

88 TD = Passing **DT2 = TV Monitor**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	444212	222106	1.56	0.2191
SN(GRP)	51	7242150	142003		

TARGET RECOGNITION DISTANCE

88 TD = Passing

DT3 = Cinematic Projection

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	297692	148846	0.68	0.5107
SN(GRP)	53	11590414	218687		

TARGET RECOGNITION DISTANCE

89 TD = Entering Freeway

DT1 = Video Projection

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	52457	26228	1.57	0.2150
SN(GRP)	72	1202699	16704		

TARGET RECOGNITION DISTANCE

89 TD = Entering Freeway

DT2 = TV Monitor

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	8614	4307	0.37	0.6933
SN(GRP)	64	748360	11693		

TARGET RECOGNITION DISTANCE

89 TD = Entering Freeway **DT3 = Cinematic Projection**

Source	DF	Type III SS	Mean Square	F Value	p
GRP	2	65822	32911	8.00	0.0008
SN(GRP)	65	267394	4114		

APPENDIX F. CROSSCUTTING ISSUES ADDRESSED IN THIS REPORT

Report Section	Broad Issues							
	Age groupings/ performance hetero-geneity of test sample	Functional measures			Operational and situational factors	Accident types addressed in research	Environmental issues	Appli-cations of research findings
		Sensory/ perceptual functions	Cognitive processes	Psychomotor response				
BACKGROUND INFORMATION		pp. 3-5	pp. 3-4	p. 17	p. 3	pp. 4-18	pp. 4, 7-14, 17	
SAMPLE SELECTION	p. 29	pp. 30-32	pp. 32-37					
MOTION JUDGMENT EXPERIMENTS	pp. 51-78	pp. 51-78	pp. 51-78	pp. 47-48	pp. 39-51			
GAP ACCEPTANCE EXPERIMENTS	pp. 85-107 p. 102	pp. 85-107 p. 103	pp. 85-107 p. 103		pp. 79-82 pp. 83-85 pp. 105-107	pp. 79-80		
COUNTERMEASURES IDENTIFICATION		p. 109				pp. 110-120		pp. 109-120
CONCLUSIONS AND RECOMMENDATIONS	pp. 121-123	pp. 121-122			pp. 123-124	pp. 121-124		p. 122

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