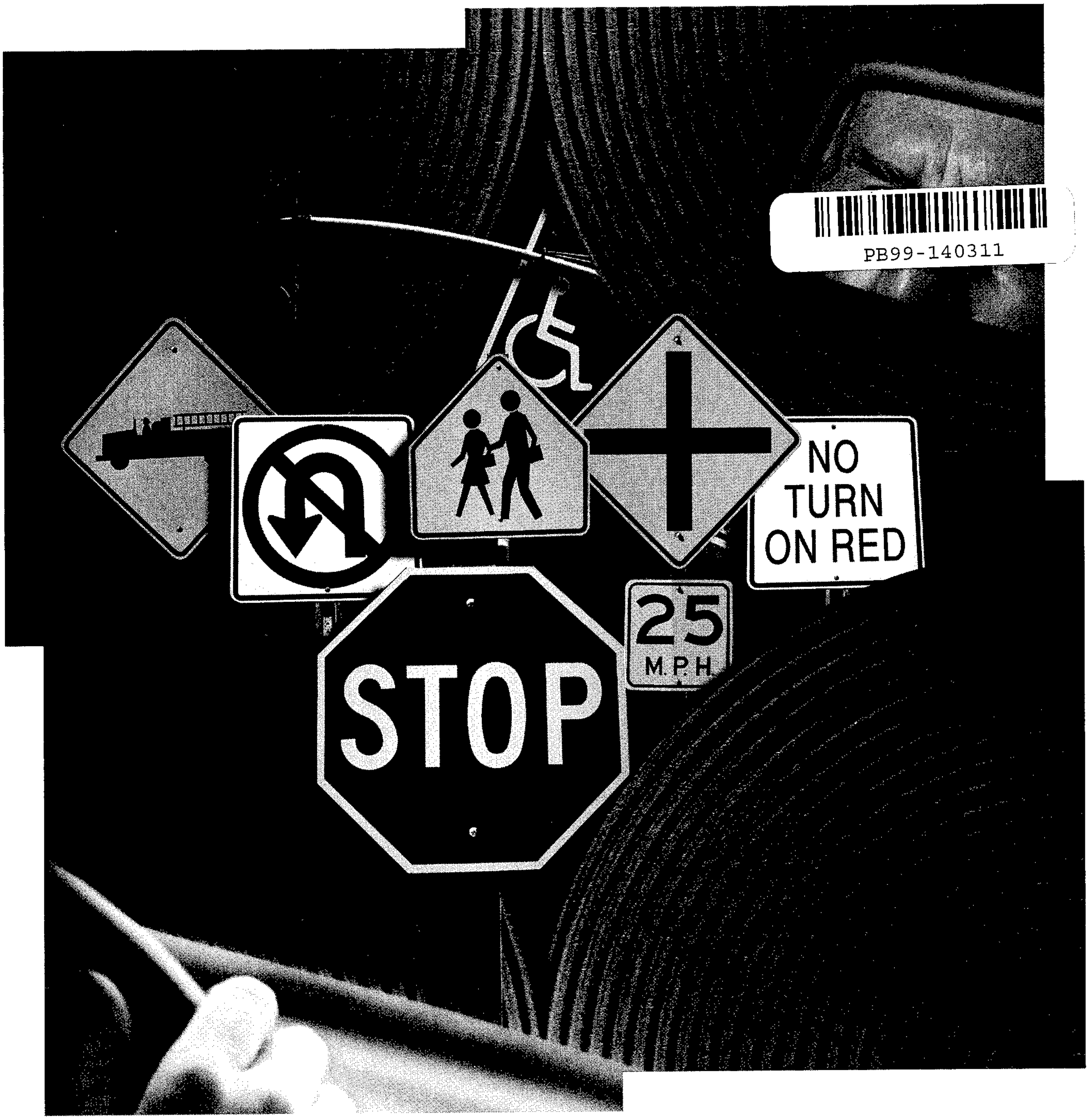

Intersection Negotiation Problems of Older Drivers

VOLUME II: BACKGROUND SYNTHESIS ON AGE AND INTERSECTION DRIVING DIFFICULTIES

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16. Abstract

This project included a background literature synthesis and observational field study. The research goals were to document driving problems and errors at intersections, for older drivers using their own cars to travel familiar and unfamiliar routes, and to measure how well they could be predicted by prior tests given in an office setting. Volume I presents the field study methodology and results; Volume II presents the background synthesis.

Field observations of intersection negotiation were conducted using 82 subjects, age 61 and older, referred to the California Department of Motor Vehicles for special testing. The subjects first completed a functional test battery measuring vision, attention capabilities, and head/neck flexibility. They then underwent on-road testing administered by DMV examiners. Subjects were administered the test on both an unfamiliar and familiar route, unless the testing was prematurely terminated for safety reasons. During the on-road tests, a miniature, multiple-camera apparatus in the driver's own vehicle recorded visual search behaviors, brake and accelerator use, and traffic events in the forward scene. Analysis of the videotaped data revealed a high incidence of visual search errors. Many common behaviors were included (such as failure to look to the sides when traveling through an intersection on a green light) that were technical errors, but which rarely require an emergency response. The highest error rate for an actual maneuver, as captured by the cameras, was making a lane change with an unsafe gap. This problem was exaggerated on the low familiarity test route, where drivers had no expectation of where the next turn would occur. Analysis of errors recorded by the DMV examiners followed the same general pattern as the video-based error classification, where scanning errors predominated across both familiar and unfamiliar test routes, and maneuver errors occurred less frequently. Those driving errors observed most often by the examiners included failure to stop completely at a stop sign, stopping over a stop bar, improper turning path, and stopping for no reason. Regression analyses examined the relationships between functional test results and weighted examiners' error scores. Speed of response on visual discrimination tasks was the best predictor, but no single measure accounted for more than 18% of variance on the criterion.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

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

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

(Revised September 1993)

VOLUME II: BACKGROUND SYNTHESIS ON AGE AND INTERSECTION DRIVING DIFFICULTIES

TABLE OF CONTENTS

VOLUME II: BACKGROUND SYNTHESIS ON AGE AND INTERSECTION DRIVING DIFFICULTIES

LIST OF FIGURES

VOLUME II: BACKGROUND SYNTHESIS ON AGE AND INTERSECTION DRIVING DIFFICULTIES

LIST OF TABLES

INTRODUCTION

A central objective at the outset of this project was to identify and prioritize—in terms of likely consequences for safe driving performance at intersections—the age-related decrements in functional capability that can be linked through empirical evidence or logical inference to increased crash risk. This objective was addressed through a survey of selected research topics and consultations with experts in the field. The research topics of principal interest were: (1) age differences in functional capabilities of potential importance to the safe negotiation of intersections; (2) the relative overinvolvement of older drivers in specific crash types at intersections, and specific unsafe behaviors identified as causal or contributing factors; and (3) the critical driving task demands for identified maneuvers at designated intersection types, with assignments of relative (increased) risk for older drivers based upon mismatches between situational demands and drivers' (diminished) response capabilities. A table summarizing the expert consultations in this project activity is included at the end of this section.

To guide this effort, a conceptual framework was developed expressing the hypothesized relationship between intersection crash risk and age differences in functional capabilities. This framework, as diagrammed in Figure 1, assumes that the aging-crash risk relationship is mediated through unsafe driving behaviors which, by implication, can be reliably observed and quantified as a basis of comparison across individuals and across situations.

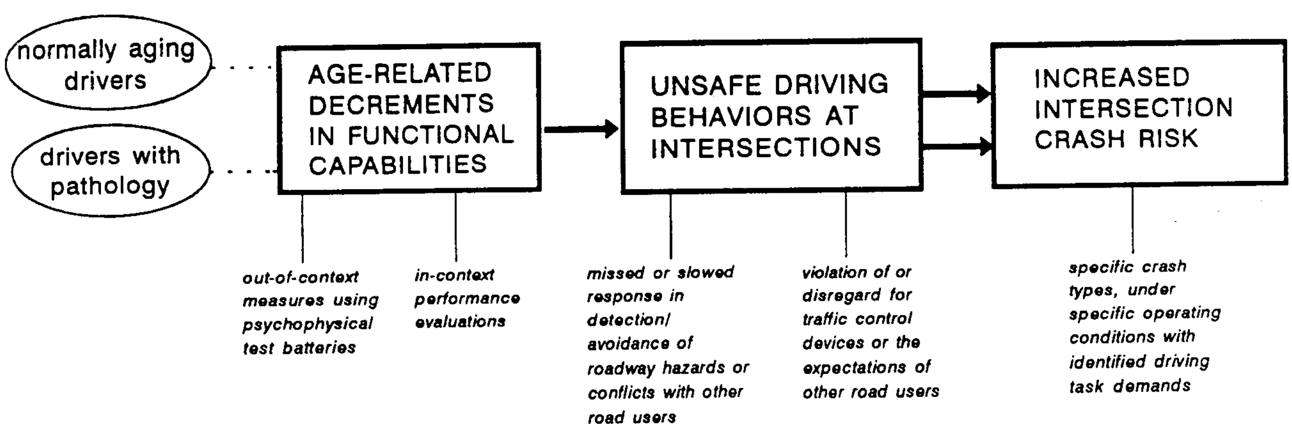

Figure 1. Hypothesized relationship between intersection crash risk and age differences in functional capabilities, mediated through unsafe driving behaviors.

Age-related functional changes of interest in the present review include those indicated both by "out-of-context" measures obtained in clinical/laboratory assessments, and by measures obtained using simulation or under closed-course or real-world driving conditions. Materials reviewed were selected from the burgeoning catalogue of (cross-sectional) studies on aging, on the basis of the presumed criticality of the functional deficits described therein to safe and effective driving performance at intersections. Such presumptions are underscored in this discussion through frequent references to specific task demands for intersection negotiation. The diagnosis, symptoms and consequences for safe driving performance of dementing illness, which afflicts a disproportionate number of older persons, are also addressed.

Prior analyses of intersection crashes were reviewed to document age differences in relative involvement rates for particular types of crashes. This information is important because it can lead directly to a specification of the vehicle maneuvers for which older drivers most often experience performance failures at intersections. For the various maneuvers, requirements for drivers' behavioral responses may then be identified, suggesting surrogates for crash risk which include, for example, (1) missed or slowed responses by drivers in the detection and/or avoidance of roadway hazards or conflicts with other road users, and (b) the violation of, or disregard for, traffic control devices or the expectations of other road users.

Building upon the review of literature and intersection crash analyses, a modified task analysis examined the critical driving task demands for specific intersection types under specific operating conditions, highlighting mismatches between situational demands and drivers' behavioral responses likely to result due to age-related diminished capabilities. Since the literature contains a dearth of controlled, *prospective* studies directly linking age-related diminished capabilities to differential crash involvements, and thus to increased crash risk at intersections, this task analysis inferred probable safety outcomes according to the following logic: where a specific functional decrement negatively influences the speed or accuracy of performance of a critical driving task, the safe negotiation of intersections whose features are associated with particular performance demands will be compromised, resulting in a higher incidence of unsafe driving behaviors and increased crash risk. As a result of this effort, problems in the negotiation of intersections by older drivers were prioritized according to their likelihood of occurrence and their consequences for traffic safety.

The consultations with experts contributing to this background synthesis solicited input in the form of published and unpublished research reports and personal communications. These were integrated, where appropriate, into each discussion topic addressed in the review. These contributions are acknowledged and summarized in Table 1.

Table 1. Status and content of expert consultations.

Name	Expertise	Input provided re:
Dr. Karlene Ball Department of Psychology Western Kentucky University Bowling Green, KY	Research Design; Accident Analysis; Clinical Assessment; On-Road Evaluation	• Availability of raw data from measures collected at WKU (UFOV, MOMSSE, Trails-B, CS, visual fields, etc). • Availability of reprints of older driver intersection accident studies conducted at WKU. • Suggestions for measuring situation detection and visual search behaviors (measure "looked but did not see" by correlating videotaped eye movements with driver behavior). • Suggestion to use a test vehicle outfitted with dual brakes, instead of allowing participant to drive own vehicle. • Suggestion to evaluate both impaired and nonimpaired sample in the same manner (with trained evaluator in front seat and observer(s) in back seat).
Ms. Amy Campbell Occupational Therapy Department Gaylord Hospital Wallingford, CT	Clinical Assessment; On-Road Evaluation	• Superiority of driving simulation to predict on-road driving performance over paper and pencil tests. • Use of the EDS to obtain measures of functional capability. • Use of the Pelli-Robson letter sensitivity chart as a candidate predictor variable. • Observed problem driving behaviors.
Mr. Brian Ellison Department of Transport MAVIS Transport Research Laboratory Crowthorne Berkshire, UK	On-Road Evaluation	• Executive summary of a study recently conducted to determine the characteristics and driving patterns of drivers aged 70+. • Notes on MAVIS Driving Ability Assessment.
Dr. Jaime Fitten VA Medical Center Geropsychology Sepulveda, CA	Geriatric Psychologist	• Importance of screening for dementia, as its presence would indicate a higher accident involvement. Suggested tests include Folstein Mini Mental Status, clock drawing, Folstein Test for Memory and Trails-B. • Realization that a person may score normal on Mini Mental Status, and still show diminished driving performance (need to know what degree of cognitive impairment our subjects have). • Importance of making the test vehicle seem as normal as possible (i.e., conceal as much equipment as possible), to prevent performance anxiety, which would be especially prevalent among the cognitively impaired.
Dr. Rosamond Gianutsos Cognitive Rehabilitation Services Sunnyside, NY	Research Design; Clinical Assessment	• Arguments for including the EDS, Dynamic Binocular Function, Visual Fields, and Visual Selective Attention in the test battery to assess functional capabilities. • Arguments against the use of Auditory Selective Attention, and Forward and Reverse Digit Span in test battery. • Caution about adhering to test protocols and in allowing enough practice time. • Pertinent research articles on EDS and computerized screening tests for evaluation of cognitive abilities.

Table 1 (Cont'd). Status and content of expert consultations.

Name	Expertise	Input provided re:
Ms. Susan Henderson Driver Rehabilitation Services-RTC Memorial Hospital South Bend, IN	Clinical Assessment; On-Road Evaluation	• On-road assessments may be affected by time of day, day of week, and weather conditions. • Patients with field neglect due to stroke often have problems in their search and scan patterns (they don't know when and where to look) and includes not scanning mirrors and over the shoulder. • Stopping distance problems are frequently observed where older drivers must stop abruptly at the end of breaking, to avoid rear-end collisions (closing distance perception problems). • Yielding right of way seems to be a problem of not having adjusted to the larger volumes of traffic on the roads today and not taking into account their diminished capabilities. • Importance of collecting background information /demographics; professional drivers may be able to perform better despite their injuries because safe driving practices have become an ingrained habit. Also, gender may be a variable as women typically drive fewer miles and have less experience in these age groups. • Effect of videotaping on driver performance. • Usefulness of peripheral vision tests to indicate whether subjects fail to acknowledge a particular side. • Importance of consistency in giving instructions in on-road evaluation (i.e., do you repeat instructions? If so, how many times?)
Dr. Mary Janke R & D Section, F-126 California Department of Motor Vehicles Sacramento, CA	Research Design; Accident Analysis	• Current NHTSA project "Age-related disabilities that may impair driving and their assessment." • Referral to David Hennessy at CALDMV for preliminary results of ability of test battery to predict accidents.
Dr. Richard Marottoli Yale University School of Medicine Geriatric Assessment New Haven, CT	Attending Physician, Geriatric Assessment	• Consideration of using DMV records to help tie specific actions to increased accident risk. • Concern about whether differences between groups will be large enough to distinguish them on performance measures, and concern about whether sample size is large enough. • Consider performing same evaluation on both groups. • Concern about whether unobtrusive evaluation will really go unnoticed by the subject. Knowing that performance is being observed may affect it, either positively or negatively. • Acceptability of using Folstein Test (mental status) and UFOV and Trails-B (selective/divided attention).
Dr. Philip Oxley Cranfield Centre for Logistics and Transportation Cranfield Bedford, England	Coordinator of EDDIT (Elderly Drivers and Information Telematics)	• EDDIT reports on driving behavior and accident characteristics of elderly drivers. • Protocol for EDDIT simulator trials testing older drivers' behavior when turning left across on-coming traffic.
Dr. Sheldon Retchin Medical College of Virginia Richmond, VA	Geriatrician	• Use of a series of tests measuring mental status, ranging from simple to complex, beginning with Mini Mental Status Exam. • Use of measures of attention. • Superiority of case-controlled design over our present sampling strategy. Choose people who have already had intersection accidents and compare their performance on functional tests to people who have had no interaction accidents. • Concern about whether "impaired" sample will truly be impaired and normal sample will not be impaired (i.e., will the differences between the sample be large enough?) and concern about size of sample.

Table 1 (Cont'd). Status and content of expert consultations.

Name	Expertise	Input provided re:
Ms. Carmella Strano Moss Rehabilitation Hospital Philadelphia, PA	Research Design; Clinical Assessment; On-Road Evaluation	• Strategies for obtaining unobtrusive measures of driving behavior of impaired sample.
Dr. Janet Szlyk Ophthalmology and Visual Sciences University of Illinois at Chicago College of Medicine Chicago, IL	Research Design; Accident Analysis; Clinical Assessment;	• Articles for inclusion in review of literature on vision and driving. • Measurement and videotaping of head/eye movements: there is a relationship between head movements and on-road accidents. • Relationship between simulator performance indices (lane boundary crossings, variability in lane position, brake pedal pressure, reaction time) and real world accident history. • Consideration of using previous accident history as an analysis variable. • Importance of researchers collecting a standardized package of background info on their subjects to enable them to relate results to exposure (i.e., older patients with some visual disorders show very poor performance on simulator and road tests, yet they have fewer accidents according to state records. Either they are driving less overall, or driving less frequently in unfamiliar areas. Paper and pencil tests will show these people take less risks, but we need to know how they are compensating.)
Dr. Karen Tallman Clinic for Alzheimers Disease University Hospital VBC Site British Columbia Canada	Clinical Assessment	• Final Report for NHRDP "Driving performance in the cognitively impaired elderly."
Dr. Lori Temple Department of Psychology University of Nevada, Las Vegas Las Vegas, NV	Research Design; Accident Analysis; Clinical Assessment; On-Road Evaluation	• Manuscript "Driving Ability: The Role of Perceptual and Cognitive Factors," to assist in the selection of predictors.
Dr. Otto von Mering Center for Gerontological studies University of Florida Gainesville, FL	Gerontology/Anthropology	• Draft report from CGS research program (Driving and the Elderly American: A Quality of Life Issue). • Literature describing sociological perspectives on aging. • Use the opportunity to collect info. about subjects' orientation to risk-taking (i.e., habitual perspective & reliance on "maximizing-the-minimum-risk" vs the so-called 'rational' "minimizing-the-maximum risk", as this may constitute a potential intervening if not confounding variable in the research.
Dr. Robert Wallace Preventative Medicine and Envir. Health University of Iowa Iowa City, IA	Epidemiologist	• Concern about whether the non-impaired sample is really unimpaired; reliance on PennDOT determination will lead to non-generalizable and uninterpretable data. To categorize subjects into one or the other will require a clear determination of health status, and physical and cognitive abilities. • Precise definitions of "frailty" are required as frailty due to emphysema or arthritis would yield different results than muscle weakness and slowness due to medications. • Assurance that the current health status of a subject is stable is required, so performance is reflective of the participant's usual capacities. • Control for years of driving and accident record, so that skill level becomes a variable to analyze. • Equipment on the roof of the following vehicle may lead to an unnatural testing environment.

AGE DIFFERENCES IN FUNCTIONAL CAPABILITIES

Older persons disproportionately manifest a variety of measurable functional deficits with high construct validity as predictors of driving difficulty and therefore, presumably, of crash risk. While the *empirical* validity of such age differences as crash predictors remains at issue, a number of retrospective studies have established significant correlations between functional deficits and crash involvement. The following discussion explores the nature of deficits in sensory/perceptual, cognitive, and physical functions which appear with increasing frequency—whether the result of normative aging, trauma, disease, or dementia—among older persons, and the potential effects of such deficits on driving performance at intersections. In addition, a limited set of studies has been sampled to report older drivers' self-perceptions regarding the problems they experience as a result of diminished functional capabilities.

Briefly, the relationships between functional capabilities of older drivers and intersection negotiation likely to be of greatest operational significance can be summed up as follows. Age-related declines in spatial vision, including acuity (both static and dynamic) plus low- and mid-, as well as high-frequency spatial contrast sensitivity, will delay recognition of intersection features such as pavement width transitions, channelized turning lanes, island and median features across the intersection, and any nonreflectorized raised elements, and will delay comprehension of the information provided by pavement markings and traffic signs. This information loss in the early stages of the driver's vehicle control task will be compounded by attentional and decision-making deficits shown to increase with increasing age, with age differences in performance magnified as serial processing demands for conflict avoidance and compliance with traffic control messages increase during the intersection approach. Age-related decrements in the "useful field of view," selective attention, and divided attention/attention switching capabilities will slow the initiation of a driver's response when a lane change or other change of heading is required, either for hazard avoidance or to accomplish a desired intersection maneuver. In addition, less efficient working memory processes will translate into riskier operations for older drivers at intersections with increasing geometric complexity, and/or intersections in unfamiliar areas where concurrent search for and recognition of navigational cues disproportionately taxes "spare capacity" for lane-keeping and conflict avoidance. For turning drivers, an age-related diminished capability in judging the "least safe gap" ahead of oncoming vehicles may lead to inappropriate maneuvers. Finally, the execution of vehicle turning movements becomes more difficult for older drivers as bone and muscle mass decrease, joint flexibility is lost, and range of motion diminishes. Simple reaction time, while not significantly slower for older drivers responding to expected stimuli under nominal operating conditions, suffers operationally significant decrements with each additional response to an unexpected stimulus, i.e., as required in emergency situations.

DIMINISHED SENSORY/PERCEPTUAL CAPABILITIES

To respond appropriately to all manner of stimuli in the roadway environment, a driver must first detect and recognize physical features of the roadway, traffic control devices, other vehicles, pedestrians, and a wide variety of other objects and potential hazards of a static and dynamic nature. On rare occasions, critical information concerning the presence or position of traffic is conveyed to a road user solely through an auditory signal; in the vast majority of cases, however, the visual system is preeminent at this (input) stage of processing.

It should be emphasized at this point that the classification of older individuals as visually impaired, from a human factors perspective, depends very much on the context of expected performance. For example, many individuals who are seriously affected by presbyopia (farsightedness), to the point of not being able to read without strong corrective lenses, may be relatively unaffected in viewing objects at a distance while driving. In another example, glare from ocular media scatter may pose serious problems at night, in rain or in bright sunlight but presents little difficulty on mildly overcast days. Nevertheless, a very high proportion of drivers age 60 and older will show a serious limitation in visual performance under at least *some* typical driving conditions. If even as small a group as the lowest-scoring-25 percent on critical functional tests are considered impaired, this number added to those experiencing clinical pathology gives an estimate of 1 in every 3 drivers over age 60 as potentially seriously impaired (Staplin, Breton, Haimo, Farber, and Byrnes, 1986).

The visual sensory input system is a complex biological composite of optical and neural components, including the cornea, aqueous humor, iris, lens, vitreous body, and retina. All of these elements change with age in ways that interact with each other and cause deterioration of visual performance. However, the largest single factor contributing to declining visual performance in the non-pathologic eye is increased light absorption and scattering in the crystalline lens. A distant second as a contributing factor is deterioration in the structures of the retina and neural pathway. All other factors, apart from pathology, may be grouped as minor in overall impact (Staplin, Breton, Haimo, Farber, and Byrnes, 1986). Physiological changes with aging in the lens and retina, and the most significant age-related visual pathologies, are summarized below before a detailed consideration of performance measures used to assess functional decline in the visual system.

The lens of the eye is a mechanically dynamic structure transparent to the visible spectrum, whose function is to focus an image clearly onto the neural retina where the process of seeing is initiated. Compared to the cornea and aqueous, the lens shows substantial changes with age that have serious consequences for visual performance (Spector and Sigelman, 1974; Spector, 1982). Its continued transparency during life is obviously critical to continued adequate visual performance. Two important changes in the lens occur as a function of normal aging. First, the lens grows constantly thicker and less able to contract in the act of accommodation for focusing on near objects. This causes the near focal point to continuously move out throughout life, eventually necessitating the use of reading glasses. The reduced elasticity that accompanies thickening also may slow down the act of accommodating to new targets nearer to the eye, although accommodation to view objects farther away appears less affected (Allen, 1956). Second, the lens becomes more yellow with age, indicating increased light absorption in a lens pigment that differentially absorbs short wavelength (blue) light.

Neither the reduced ability to accommodate to near objects, nor the slower speed of accommodation as an older individual's focus shifts to/from near versus far objects, can be reliably linked in the technical literature to impaired performance on specific driving tasks. Research on other effects of age-related increases in lens density deserve mention, however.

First, studies have indicated a very large age difference in spectral absorption of blue light compared to that for wavelengths longer than 500 nanometers (nm). With aging, the entire absorption curve moves up, so that disproportionately less blue light gets through to the retina and the lens takes on a yellowish appearance. A documentable effect of the yellowing lens is a reduced ability to discriminate colors in the blue spectral region. This color defect shows up on a test such as the Farnsworth-Munsell 100-hue test as an increase in errors along a blue-yellow error axis (Verriest, 1963; Knoblauch, Podgor, Kusuda, Saunders, Hynes, Higgins, and DeMonasterio, 1986). The consequence for driving of a loss of color discrimination in the blue-yellow range is probably not great, even for very old and dense lenses. However, it could be expected that the more moderate increase in density for the longer wavelengths would lead eventually to significant reduction in the proportion of incident light penetrating to the retina, which could then be of serious consequence to driving performances in low light or low contrast situations.

The sudden formation of opacities in the form of cataracts in the lens is of much greater consequence than the slower physiological changes described above. A cataract results when protein particles in the lens increase in size to the point of producing significant light scatter. The cataract develops relatively quickly (1 to 5 years) compared to the slower lifelong changes in blue light absorption (Chylack, 1978). The major effect of the cataract on light is to back-reflect and scatter it. Back-reflection in a dense cataract may drastically reduce the proportion of incident light reaching the retina (Sigelman, Trokel, and Spector, 1974), but even less dense cataracts may reduce the contrast of the retinal image to a significant degree. A patient with a diffuse sclerotic cataract with daytime visual acuity of 20/25 will complain of glare in bright sunlight and may have difficulty seeing when looking into the headlights of an oncoming car at night. According to a recent review, there are no reliable data describing systematic effects of different levels of severity of cataracts on driving performance (Klein, 1991).

The retina is the multi-layered, innermost membrane of the eye that contains the initial neural substrate of vision, and is by far the most complex element of the visual system. Of all retinal changes with age, the most prevalent is the appearance of clinically-evident drusen (i.e., an accumulation of lipofuscin, a metabolic byproduct of outer segment renewal) in the retinas of 30 to 50 percent of individuals over the age of 60 (Feeney, Berman, and Rothman, 1980; Macular Phocoagulation Study Group, 1982). Between 1 and 5 percent of these persons go on to develop the pathological condition of senile macular degeneration (SMD), which is the leading cause of blindness in the over-60 age group (more people have glaucoma and cataracts, but fewer end up blind). Although people with age-related macular degeneration do not usually lose all of their sight, because of loss of central vision, they may be incapable of reading road signs or be unable to see cars (Klein, 1991).

Other important retinal pathologies include diabetic retinopathy and retinal artery and vein occlusions, all of which increase in frequency in old age. In diabetic retinopathy, chronic deterioration of retinal vascular support as a byproduct of the diabetic condition can lead to ischemia (insufficient blood flow), which in turn stimulates pathologic generation of new blood vessels. Color vision may be affected, with loss of the ability to discriminate yellow and blue. Additionally, contrast sensitivity may be affected, with losses across all spatial frequencies as retinopathy progresses (Klein, 1991). This process ultimately leads to vascular disorganization, hemorrhage and blindness. Similarly, blockage of venous or arterial flow can also stimulate vascular growth and the associated complications, which may seriously compromise vision. The diabetic situation is clearly in the chronic disease category, while vein and artery blockage appears more as an extension of the normal aging process.

Finally, a pathologic condition with relevance to driving found with increasing frequency among older persons is high interocular pressure (IOP), leading to glaucoma. Glaucoma eventually results in destruction of optic nerve fibers and is the second leading cause of blindness in older patients, affecting about 1 percent of those over age 60 (Greenberg and Branch, 1982; Viggosson, Bjornsson, and Ingvason, 1986). The condition is painless and patients are often unaware that they are suffering any deficits in visual field. There is a gradual constriction in the peripheral visual field, which can result in a total loss of vision. Drivers suffering from open-angle glaucoma and peripheral visual field loss may have difficulty seeing cars or pedestrians approaching from the side, and may show reduced contrast sensitivity (Klein, 1991).

Turning to performance effects of the aging eye, assessment techniques common to visual psychophysics provide a variety of tools that can be used to define the status of an intact visual system. Information provided by these functional assessments must then be evaluated in light of what is known of the relevant visual factors present in the driving situation. It is not always easy to make the connection between test performance and driving performance; the relative importance of performance factors such as image sharpness, glare, contrast and color can vary enormously depending upon such factors in the driving environment as the presence of rain, wet surfaces, frost, night, twilight or daylight conditions. These problems notwithstanding, functional tests in the following categories provide the best available information on performance of the aging visual system as it may relate to intersection driving: (1) spatial vision; (2) visual fields; (3) depth and motion perception; and (4) dark adaptation and glare recovery functions. A fifth category—(5) color vision—is deemed of lesser importance to the safe negotiation of intersections, but receives comment below. Accordingly, the following material will address each of the five categories of visual performance named above, presenting evidence of age differences in functional capability and citing studies of the effects of such differences on driving performance.

Spatial Vision

This category of vision assessment includes standard high contrast acuity testing, measurement of spatial contrast sensitivity or modulation transfer functions (MTFs), and the measurement of absolute and increment visual thresholds. The most systematic method for testing spatial vision is through determination of contrast sensitivity thresholds for a full range of sine wave gratings. A plot of contrast threshold against spatial frequency then produces a modulation transfer function (MTF), which can be used to infer performance for any arbitrary stimulus configuration. Contrast sensitivity measurements can also be made at a specific spatial frequency of interest; the 4-minute gap size of a Landolt-C test stimulus as employed in many of the assessments reported in CIE Publication 19/2 (CIE, 1981) is an example of this test approach.

The characteristic MTF for spatial vision shows an inverted U-shaped function with peak sensitivity at an intermediate frequency. The cutoff of this function at the high frequency end depends on factors such as illumination and target size, and ranges from 15 to about 25 cycles per degree (c/deg) for foveal viewing at moderate illuminances (Campbell and Robson, 1968). When viewing conditions are kept constant and factors such as pupil size variation are taken into account, high and middle spatial frequency performance is found to decline with age, especially over age 40 (Derefeldt, Lennerstrand, and Lundh, 1979; Owsley, Sekuler, and Siemsen, 1983). Also, it has been shown that increased lens absorption with age alone cannot account for this decline in performance (Owsley, Gardner, Sekuler, and Lieberman, 1985).

Another, more widely examined aspect of spatial vision is acuity. Visual acuity is a test of high frequency spatial response at contrast levels far above threshold. Instead of measuring contrast threshold as a function of spatial frequency, acuity tasks measure the threshold spatial resolving power of the visual system—i.e., what separation is necessary in order to distinguish two high contrast features as being separate. In general, acuity performance can be predicted from high spatial frequency contrast sensitivity, but the converse is not true. Thus, it is not surprising that visual acuity, like high spatial frequency response, declines slowly at first, beginning at approximately age 40, then after the age of about 60 the decline accelerates (Weymouth, 1960; Richards, 1966; Richards, 1972). The Framingham study (Kahn, Leibowitz, Ganley, Kini, Colton, Nickerson, and Dawber, 1977) has provided evidence that about 10 percent of men and women between ages 65 and 74 have acuity worse than 20/30, compared to roughly 30 percent over the age of 75.

Dating at least back to Burg (1966), investigators have concentrated upon hypothesized relationships between acuity and driving competence. These studies have on the whole been quite disappointing, insofar as correlations between the driving record and static acuity scores are concerned. The ability of an observer to resolve moving targets—i.e., *dynamic* visual acuity (DVA)—has been found to have a stronger relationship with performance in many applied settings, however (Morrison, 1980; Long and Crambert, 1990). Shinar and Schieber (1991) point out that DVA may correlate more strongly with crash involvement, and especially among older drivers, because it combines multiple visual sensory and motor skills necessary for safe driving.

An investigation using the Pelli-Robson chart, which measures contrast sensitivity using letter stimuli that decrease in contrast but not in size, examined 1,475 ITT Hartford insurance policyholders' driving history data for differences in at-fault crash involvement (Pelli, Robson, and Wilkins, 1988). Contrast sensitivity was negatively correlated with at-fault crashes (r = -0.11); in addition, the researchers noted that since contrast sensitivity was negatively correlated with age itself (r = -0.40), the relationship between performance on the Pelli-Robson chart and crash involvement was probably understated (Brown, Greaney, Mitchel, and Lee, 1993).

In a study conducted to determine whether age-related differences in the ability to read highway signs could be measured by contrast sensitivity performance, Evans and Ginsburg (1985) used their own test chart—i.e., Vistech VCTS 6500—to obtain binocular contrast sensitivity measurements of 13 younger observers (ages 19 to 30) and seven older observers (ages 55 to 79) at spatial frequencies of 0.75, 1.5, 3.0, 6.0, 12.0, and 24 cycles per degree (cpd), while also measuring Snellen visual acuity. Observers then performed a highway sign discrimination task requiring each observer to view a movie film projection of an approaching road sign designating either a cross (+) or T intersection. The dependent variable was the discrimination distance for correct responses. Results showed that the difference in road sign discrimination distance was statistically significant; older drivers had to be significantly closer to the highway sign to determine whether it denoted a cross or T intersection, with a 25 percent average discrimination distance between the younger and older groups. The older group showed significantly lower contrast sensitivity than the younger group at 3.0, 6.0, and 12.0 cpd; significant correlations between highway sign discrimination distance and contrast sensitivity were shown at 1.5 and 12 cpd. There was no significant difference between Snellen acuities of each age group, and no significant correlation between Snellen acuity and discrimination distance.

A more recent study of the visibility distance of highway signs among young, middle-aged, and older observers by Kline, Ghali, Kline and Brown (1990) included the finding that icon signs provided superior visibility distances over text signs, particularly under dusk conditions. These authors suggested that older drivers may benefit disproportionately from the use of icon signs particularly at night, given their self-reported difficulties with signs and markings under conditions of low illumination. Advisory signs indicating proper lane position for specific maneuvers at intersections fall within this category. In an older driver survey by Yee (1985), 40 percent of the respondents reported that they *never* had difficulty reading traffic signs before they were too close to do any good; 33 percent *seldom* had difficulty reading them, and 24 percent *sometimes* did. Difficulty with traffic signs occurred most often on city streets (36 percent)—including signing at intersections—or on freeways through cities (31 percent).

More generally, a field investigation (Sivak, Olson, and Pastalan, 1981) of the effect of driver's age on nighttime legibility of highway signs indicated that older subjects perform substantially worse than younger subjects on a nighttime legibility task using a wide range of currently available sign materials. When subjects in two age groups (under age 25 and over age 61) were matched on high luminance visual acuity, the demonstrated legibility distances for the older subjects were only 65 to 75 percent of those for the younger subjects. These researchers concluded that age-related performance decrements on nighttime legibility tasks are primarily the result of sensory (visual acuity) deficits, rather than shortcomings in higher information-processing (e.g., reading/comprehension) skills (Sivak and Olson, 1982).

Aside from difficulties in the use of signing, problems for older drivers at intersections most likely to result from (age-related) deficits in spatial vision relate to the timely detection and recognition of pavement markings and delineation of curblines, medians, turning islands, and other intersection features. In a pertinent laboratory study, two groups of subjects (ages 19-49 and 65-80) viewing a series of ascending brightness and descending brightness delineation targets were asked to report when they could just detect a roadway heading (either left or right) from simulated distances of 30.5 and 61 meters (100 and 200 ft) (Staplin, Lococo, and Sim, 1990). Results showed that the older driver group required a contrast of 20 percent higher than the younger driver group to achieve the discrimination task in this study.

The comparative abilities of younger and older drivers to recognize downstream pavement markings has also been modeled extensively using the DETECT and PCDETECT programs developed by the Ford Motor Company (Bhise, McMahan and Farber, 1976). Analyses conducted for the Federal Highway Administration (Staplin et al., 1990) and for Transport Canada (ADI, 1991) using these computer models yield results consistent with related empirical studies: the age-related decline in spatial vision predicts delineation recognition ability for the best-performing quartile of the normative older (age 75+) driver population that is roughly equivalent to the poorest-performing quartile of the youngest (ages 18-35) driver group.

In summary, the attempt to relate studies of spatial vision functions to driving performance—with or without driver age as an independent variable—has been almost exclusively preoccupied with traffic control device (TCD) design elements, where high frequency cues predominate. Extrapolations of findings in the functional assessment literature to other intersection features must also give significant weight to the data describing drivers' response to mid- and low-frequency cues, however; age-related declines in contrast sensitivity also grow markedly for stimuli in the spatial frequency range below 12 cpd. Crucial issues in this regard include the timely and accurate perception of median and pavement edge boundaries which provide path guidance during the approach to and at intersections. Shifts in alignment, lane width transitions, and turning bays should be perceived at least at a 5-second preview distance. And, a particular need exists for left-turning drivers to pinpoint the exact location of islands, abutments, or other raised features across the wide intersections commonly encountered on suburban arterials in the United States, often while concurrently engaged in competing "effortful" working memory tasks.

Visual Fields

Age-related changes in visual fields can be measured either as a reduction in field area (contraction of the field limits) for different target sizes and intensities, or as an elevation in threshold values at distinct locations within the field limits. A kinetic testing method (Goldmann fields) has been used almost universally until the recent introduction of computer automated static techniques. Kinetic testing employs a movable spot of white light that is detected by the subject as it is brought slowly into the field of view from a starting point beyond the field limit. Isopters, or lines of equal detectability (i.e., lines that connect points in the visual field which are equally sensitive to the presence of the test stimulus), define the field limits for a given spot size and intensity. In general, field area declines as a function of decreasing target size and intensity. Automated static perimetry measures increment thresholds independently at many locations in the visual field using a small spot of light on a uniform background. The field area tested is usually restricted compared to Goldmann testing and thus the limits of the field are not recorded. Instead, threshold elevations at discrete locations are recorded and may be averaged to report a mean threshold elevation.

Decline in field area with age for both central and peripheral isopters using the kinetic method has been demonstrated (Drance, Berry, and Hughes, 1967). Similarly, a steady rise as a function of age in the mean threshold for static fields by a factor of 3 to 5 per decade has been reported (Bebie, Fankhauser, and Spar, 1967; Haas, Flammer and Schneider, 1986; Jaffe, Alvarado, and Juster, 1986). It is probable that some of this decline in sensitivity with age is attributable to non-neural factors such as progressive senile miosis, increased lens absorption, and increased light scatter in the ocular media. However, the relative importance of each of these factors is not well established.

Evidence describing the relationship between visual field loss and driving performance is mixed. In several large-scale crash analyses it has not been possible to find a significant correlation between the extent of drivers' visual fields and crash rates (Burg, 1967, 1968; Henderson and Burg, 1974; Cole, 1979). In a more recent study including over 17,000 volunteers, however, it was found that subjects with bilateral visual field defects had rates of crashes and convictions more than twice that of age- and gender-matched controls without bilateral defects (Johnson and Keltner, 1983). A study in Sweden using a driving simulator documented large individual differences among subjects with visual field defects, with most of them demonstrating impaired detection capability for test stimuli in the affected parts of the visual field (Lovsund, Hedin, and Tornros, 1991). In addition, it is important to note that the effect of a visual field loss on driving should be strongly related to its location: defects in the central field may be generally presumed to be more important than peripheral defects, and the horizontal meridian may be assumed to be most traffic relevant.

Logically, the impact of reduced visual field size in safe intersection use will be demonstrated by poorer performance in drivers' peripheral detection of vehicles and pedestrians during merging and turning maneuvers, respectively. When the visual field is restricted, increased eye movement may be invoked as a compensatory strategy. For a standard mounting of traffic signals to the right side of an intersection, it may be demonstrated that driver eye movement distances from the signal to a left-turning crosswalk must increase as the driver approaches the crosswalk. Older drivers who may have greater difficulty maintaining rapid eye movements and associated head movements are less likely to make correct judgments on the presence of pedestrians in a crosswalk, or on their walking speed (Habib, 1980). To the extent that a specific element of geometric design places exaggerated demands on the detection of peripheral objects, given older drivers' documented loss of range and flexibility of neck rotation, age-related decline in this visual function may increase the likelihood of maneuver errors at intersections.

Tarawneh, McCoy, Bishu, and Ballard (1993) included visual field measurements provided by a Keystone telebinocular testing device in a 2-year study of 105 drivers ages 65-88 at the University of Nebraska, where a variety of mental, physical, and functional status indicators were used to account for variance in subjects' on-road driving performance, emphasizing intersection turning maneuvers. Driving performance was evaluated using the on-road Driving Performance Measurement (DPM) protocol developed at Michigan State University (Vanosdall and Rudisill, 1979). In this study, a driver education expert trained in the use of the DPM technique evaluated subjects' speed control, directional control, and visual search, as they drove in their own cars. The DPM route was a 19-km (12-mi) circuit designed to evaluate the subjects in the situations that are most often involved in the crashes of older drivers. Therefore, their performance was evaluated at seven intersections, where they were required to make left turns at five intersections and right turns at the other two intersections. Four of the left turns were made from left-turn lanes onto four-lane divided arterial streets in suburban areas, and one was made from a left-turn lane onto a two-lane one-way street in an outlying business district. Two of the left turns were controlled by protected/permitted left-turn signal phases, two were controlled by permitted left-turn signal phases, and one was uncontrolled. One of the right turns was from a turning bay at a signalized intersection onto a four-lane divided arterial street in a suburban area. The other right turn was made from a stop-sign controlled approach at the intersection of two, two-lane two-way local streets in a residential area. The speed limits on the arterial streets were between 56-72 km/h (35-45 mi/h). The speed limit in the business district and residential areas was 40 km/h (25 mi/h). In all cases, maneuver performance was evaluated for: (1) the approach to the intersection; (2) the turning maneuver itself; and (3) the departure from the intersection. Correlational analysis of the study's results revealed a significant relationship between right visual field size and driving performance ($r = 0.22$).

Gianutsos (1991) distinguishes between measures of the "functional visual field"—i.e., the area of sensitivity for an individual under ordinary viewing conditions—and measures assessing the reaction time of subjects to evaluate and confirm the presence of a given stimulus at various locations in the periphery. She recommends use of such reaction time measures to obtain an index of visual performance more useful in predicting driving difficulty than can be obtained by traditional visual field testing procedures, and has developed PC-based protocols for this purpose.

Additional relevant findings may be cited from a simulator study of peripheral visual field loss and driving impairment which also examined the actual driving records of the study participants, and used multiple regression analyses to predict both simulator crashes and real-world crashes (Szlyk, Severing, and Fishman, 1991). It was found that visual function factors, including acuity as well as visual field measures, could account for 26 percent and 6 percent of the variance in real-world and simulator crashes, respectively. When these factors were combined with simulator response indices, including deviation in lateral lane position, out-of-lane events, brake pedal pressure, and reaction distance, 71 percent of the variance in real-world crashes and 80 percent of the variance in simulator crashes could be accounted for in the study sample. Also, greater visual field loss was associated in the simulator data with greater distance traveled ("reaction distance") before responding to a peripheral stimulus (e.g., a stop sign). While age was one variable according to which experimental and control groups were matched in this research, with both groups including participants ranging in age from their late 20s to late 60s, there was no attempt in this research to account for study outcomes in terms of age *per se*. This study is noteworthy for two reasons, however. First, subjects with peripheral field loss attempted to compensate for those losses through increased lateral eye movement, a strategy that is likely to be applied less effectively as a person advances in age beyond the range included in this study. A subsequent simulator study by Szlyk, Brigell, and Seiple (1993) which did incorporate age as an independent variable similarly indicated that lateral and vertical head movements, but not eye movements, increased for patients with hemianopic visual field loss relative to an older, normally sighted group. Even more important, the authors conclude that predicting an individual's ability with regard to complex driving performance depends upon the interaction of visual and what they term "visuocognitive" variables.

In this context, it is crucial to distinguish reduced visual field size or sensitivity as a *sensory* function from the related component of visual attention commonly termed "useful field of view" (UFOV), for which reliable age differences have also been demonstrated.

This distinction will be elaborated upon in a later discussion of cognitive performance effects, where a body of evidence linking driver difficulties with intersection use, specifically, to UFOV impairments is reviewed.

Depth and Motion Perception

Tests of stereo depth perception examine a person's ability to judge relative distances without the aid of monocular cues. Arguably, a person suffering a substantial decrement in this ability may evidence difficulty in gap acceptance judgments at intersections. One recent driver performance study addressing this topic presented test slides to subjects of different age groups, which consisted of six, yellow, diamond-shaped targets, each containing four black circles. One of the four circles on each target (either the top, the bottom, the left, or the right) was designed to appear to be "floating" toward the subject while viewing the slide through the vision tester. 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. Reading the first five targets correctly (i.e., identifying the location of the floating circle) was scored as acceptable depth perception. If a subject missed two consecutive targets, the angle of stereopsis of the last correctly read target was recorded as his/her depth perception score. The mean results for three age groups (ages 18-55, ages 56-74, and age 75+) on this measure were 112, 117, and 217 seconds of arc, respectively, with standard deviations of 106, 103, and 140 (Staplin, Lococo, and Sim, 1992).

Another study utilizing a vision tester to measure depth perception (Tarawneh et al., 1993) demonstrated a significant correlation ($r = 0.35$) between this variable and intersection negotiation performance, using the DPM on-road evaluation protocol (Vanosdall and Rudisill, 1979). [NOTE: The evaluation protocol was summarized above under the discussion of age differences in peripheral visual fields.]

While accurate perception of the distance to intersection features such as islands, pedestals, and other raised features is important for the safe use of these facilities, researchers have placed a relatively greater emphasis on motion perception, where dynamic stimuli—usually other vehicles—are the primary targets of interest. Motion perception is related to dynamic visual acuity, but unlike DVA, the perception of angular motion appears to be primarily limited by age-related deficits in neural mechanisms, rather than oculomotor ones (Shinar and Schieber, 1991). Prior investigations have addressed motion perception abilities pertinent to driving, including time-to-collision and gap-acceptance judgments, though only a subset has compared older and younger subjects.

In time-to-collision (TTC) estimates drivers estimate how long it takes, moving at a constant speed, to reach specified points in their paths (Purdy, 1958). 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, (Gibson, 1966; Lee, 1974, 1976) or on a cognitive process in which TTC is estimated using speed and distance information. 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 (Schiff and Detwiler, 1979; Cavallo, Laya, and Laurent, 1986) 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.

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 ages 70 to 75 versus those ages 20 to 29 for brief (0.3 second) exposures at night. In this study, older subjects required 3.1 min of arc for detection of motion, compared to younger subjects who required only 1.43 min of arc (Hills, 1975). 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 (2.0 seconds) duration of exposure. In related experiments, older persons required significantly longer to perceive that a vehicle was moving closer at constant speed: at 31 km/h (19 mi/h), decision times increased 0.5 second between ages 20 and 75 (Hills, 1975). 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 (Hills and Johnson 1980). Specifically, Scialfa, Guzy, Liebowitz, Garvey, and Tyrrell (1991) showed that older adults tend to overestimate approaching vehicle velocities at lower speeds and underestimate at higher speeds, relative to younger adults. 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 96 km/h (60 mi/h) approach speeds—older persons accepted a gap to cross at an average constant *distance* of slightly less than 152 m (500 ft), whereas younger men allowed a constant *time* gap and, thus, increased distance at higher speeds.

Hills (1980) measured actual crossing times for 10 subjects in each age and gender group, with each driver using his/her own vehicle on a test track. Young male drivers demonstrated a much shorter mean crossing time (2.5 seconds) than any of the other classes, and younger drivers (of both genders) showed a much smaller within-subject variance than older drivers of the same gender. Darzentas, McDowell, and Cooper (1980) used the results of Hills' data in a simulation model to estimate conflict involvement for each class of subject as a function of main-road flow and speed. In the model, a conflict occurs when a poor gap acceptance decision is made by a driver, causing an oncoming vehicle to decelerate to avoid collision. The model was run for main-road flows from 500 to 900 vehicles per hour for each class of driver. In each case, the number of conflicts increased linearly with flow. Older drivers were involved in more conflicts than young drivers of the same gender, and male drivers were involved in more conflicts than females in the same age class at all flows. Crossing drivers made more judgment errors in front of faster main-road vehicles. Additionally, older drivers were more likely than younger drivers of the same gender to cause a conflict in the crossing maneuver, for a wide range of vehicle speeds.

Dark Adaptation and Glare Sensitivity

Although intersection lighting installations are common in many suburban and most urban locations, rural and/or residential settings may contain unlit intersections, and drivers' dark adaption capabilities may be tested in transitions between lit and unlit areas as well. Tests of dark adaptation of the rod and cone photoreceptors in the retina of the eye measure the improvement in threshold sensitivity with cumulative time in the dark. The normal function for a young adult shows a rapid fall in the threshold for the first few minutes followed by a brief leveling out to the cone plateau, and is then followed by a second rapid drop over 10 or 15 minutes to effectively reach the rod plateau after about 30 minutes in the dark. However, many studies have shown a progressive elevation of both rod and cone thresholds with age (McFarland, Domey, Warren and Ward, 1960; Pitts, 1982), with an accelerated loss above the age of 60 which appears to parallel the increase in lens density documented earlier in this review.

One study found that the elevation in dark-adapted thresholds with age was greatest for shorter (blue) compared to longer wavelengths, and was able to account for most of this difference in terms of increased lens density (McFarland et al., 1960). That lens density contributed strongly to the elevated thresholds in this study was demonstrated by a control group of aphakic subjects[1] who showed approximately 1 log unit more sensitivity than their natural-lens age mates (out of a 1.3 log unit difference); the remaining 0.3 log unit difference could be accounted for by pupillary and neural changes. Similarly, an earlier review concluded that about 1.5 log units out of a total threshold elevation of 2.0 from 20 to 70 years of age can be accounted for primarily by changes in the lens (1.2 log units), and somewhat less by pupillary changes (Kahn et al., 1977).

The impact for the older driver of lost sensitivity under nighttime conditions should be assessed against the nature of the night driving task. Even at night, most visual information is processed by the cone or daylight system in the foveal region; artificial lighting raises the illumination level to the photopic range so that reading and tracking functions can occur. The peripheral rod system participates primarily by alerting the driver to a weaker signal away from the foveal line of sight that may then be oriented to, with the foveal cones. The implication of a loss in rod sensitivity is that a much brighter peripheral signal will be needed to elicit proper visual attention from the driver, and that signals now falling below threshold will be ignored. In fact, the signal may need to be 10 to as much as 100 times brighter, depending on driver age and object color. Since both rod and cone thresholds increase with age, it is also true that more light will be needed to bring important tasks such as reading and tracking (path maintenance) above the cone limit. Indeed, for steadily-increasing numbers of normatively aged drivers, objects depending on reflected light for driver detection may fall close to the elevated cone threshold.

This disadvantage for the older motorist can be further compounded by environmental and/or operational conditions, and age differences in glare sensitivity and glare recovery which penalize this group. First, the stray light introduced into a driver's eyes from roadway glare sources—most notably oncoming vehicles—can create special problems for older individuals. At intersections, additional light from roadside sources and even traffic signals can create glare problems for older drivers. At relatively low pavement luminance

[1] Aphakic refers to an eye from which the lens has been removed (or was never present); eyes in which an artificial lens has been placed are termed pseudophakic.

levels, glare—or, more specifically, veiling luminance—can be treated as a contrast sensitivity reduction factor, and its effect can be compared with the direct effect of age on contrast sensitivity noted earlier.

In summary, between ages 20 and 70, aging directly reduces contrast sensitivity by a factor of about 3; older drivers are thus at a greater relative disadvantage at lower luminance levels than younger drivers. At the same time, the magnitude of the "glare factor" with respect to its detrimental effect on a 20-year-old versus a 70-year-old driver increases by a factor of about two. Assuming that the effects of age and glare on contrast sensitivity are independent, older drivers are *very* much at a disadvantage in (night) driving situations in which glare is prevalent (Farber and Matle, 1989). A study of age and the brightness of pavement edge lines referenced earlier reported that an older driver test group required a contrast of 20 percent higher than a younger group to correctly discriminate roadway heading (Staplin et al., 1990); adding glare to the identical test protocol magnified the difference in performance between the two groups, and it was observed that glare limited the ability of the older group to discriminate direction-of-curve as a function of distance to the point of curvature, but not the younger group.

Color Vision

Mediation of color vision occurs at the retinal level in a two-stage process, initiated by photon catches in the three cone types, and transformed through the middle retinal layers into two opponently coded color signals. One of the most commonly applied tests of color vision, and one of the few for which data on normal aging are available, is the Farnsworth-Munsell 100-hue test, which measures color discrimination by requiring the observer to arrange 85 very closely adjacent color samples. A number of studies document the increase in 100-hue error scores as a function of age (Verriest, 1963, Verriest, van Laetham, and Uvijls, 1982; Knoblauch et al., 1986). In these studies a differential increase in blue-yellow errors is reported for subjects with no observable ocular pathology. The mean error of this type for naive subjects over 70 years of age is greater than 100, compared to a mean error score of 37 for the 20- to 30-age decade. While the precise locus of this effect is unclear, studies of changes in color matching and wavelength discrimination performance suggest a minimal role for retinal factors in the age-related loss of blue-yellow discriminability (Ruddock, 1965; Moreland, 1978).

Driver performance studies that have examined the effects of age and color vision have keyed on motorists' responses to sign and signal elements. As one example, a laboratory study has shown that increasing driver age (in conjunction with greater numbers of signs and higher background complexity in a roadway scene) leads to increased error rates in the recognition and identification of traffic signs for the particular color combinations of white-on-green and white-on-black (Woltman, Stanton, and Stearns, 1984). Another study conducted to determine the impact of dimming traffic signals at intersections at night found that older persons have reduced levels of sensitivity to intensity and contrast, but not to color (Freedman, Davit, Staplin and Breton, 1985). Tests of color vision have been included in assessment batteries administered by Tarawneh et al. (1993), Brown et al. (1993), and Temple (1989), among others. Correlations of deficiencies in color vision with on-road driving performance were not significant and, where significant correlations with simulator performance could be demonstrated, findings have not suggested any practical consequence for performance of critical driving tasks at intersections.

In sum, age-related deficits in color sensitivity arguably may account for a statistically significant portion of the variance in the conspicuity of selected traffic sign elements, but there is no compelling reason to believe that older drivers will experience *operationally* significant differences in the overall ability to safely negotiate intersections—at least for individuals who were not anomalous during their younger and middle-aged years—specifically as the result of deficits in color vision.

Older Drivers' Self-Perceptions of Declining Visual Skills

As a complement to the empirical evidence cited above for various aspects of diminished sensory capability, the self-perceptions of older drivers themselves of problems experienced due to declining vision may be noted. Questionnaires and focus group studies have provided information about older drivers' perceptions of their visual abilities as they relate to driving, and what driving difficulties they may experience as a result of their visual impairments (Gutman and Milstein, 1988; Milstein and Gutman, 1988; Benekohal, Resende, Shim, Michaels, and Weeks, 1992; Kosnik, Sekuler, and Kline, 1990; and Klein, Klein, Fozard, Kosnik, Schieber and Sekuler, 1992). Many visual impairments occur gradually over time, and go unnoticed because the nervous system is good at "filling in the gaps" that may be missing in the visual fields. It has been shown during driving assessment and counseling, for example, that older drivers with visual field impairments *think* they can see and are aware, when in fact they are not, resulting in overconfidence in their self-appraised driving ability. When driving, such a person may be able to see the roadway, but may not perceive a cyclist on the right, an oncoming vehicle on the left, or a person in an intersection[2].

In a focus group study conducted by Gutman and Milstein (1988), the most frequently cited impairments that made driving difficult for the 162 participants *across the three age groups* studied (56-65, 66-75, and 76+) were poor vision (by 19 percent), poor night vision (by 13 percent), and glare from the sun or headlights (11.7 percent). Looking specifically at the responses of the participants age 76 and older, a greater percentage of drivers in this cohort reported difficulty with seeing at night (18.5 percent) and glare (22.2 percent) compared to drivers ages 56-65 and those ages 66-75 (Gutman and Milstein, 1988; Milstein and Gutman, 1988). Difficulty seeing/reading signs and or signals and poor vision were given as reasons for older driver crash involvement by 25 percent of the Gutman and Milstein (1988) focus group participants across the three age groups, and by 40.7 percent of those age 76 and older.

In a study to investigate whether there were differences in visual functioning between older individuals who are current drivers and older persons who have given up driving, it was found that ex-drivers had more trouble with glare when watching TV, reading small print, reading an advertisement on a passing bus, seeing clearly at dusk, and rated their

[2] Personal communication, Dr. Rosamond Gianutsos, Cognitive Rehabilitative Services, Sunnyside NY, 3/11/94.

vision as less satisfactory than their driving counterparts, regardless of age; these five questions probing these visual difficulties were significantly correlated with driving status (Kosnik, Sekuler, and Kline, 1990). Sixty-seven percent of the ex-drivers in the Kosnik et al. study gave up driving because of their visual problems, although there was no significant difference between the percentages of drivers and ex-drivers reporting glaucoma or age-related maculopathy. This study points to the fact that no single visual problem was responsible for drivers deciding to stop driving; instead former drivers exhibited declining visual abilities in several areas. Visual difficulties were comprised of loss in the overall quality of vision, performing visual tasks at a slower rate, problems locating and reading signs embedded in the cluttered surround of other signs, difficulty reading small print, trouble reading a sign on a passing bus, difficulty seeing at night, and difficulty seeing in dim light. In fact, the question with the highest correlation—reading an advertisement on a passing bus—illustrates a deficit in dynamic visual acuity. This ability, which requires the coordination of visual and motor skills, was identified in the section of this report addressing age differences in visual functions as one of the more significant performance effects of aging.

A related study surveyed adults ranging in age from 22 to 92 to gain a greater understanding of the visual difficulties they encounter while driving, as well as in the performance of everyday tasks (Kline, Kline, Fozard, Kosnik, Schieber, and Sekuler, 1992). Participants consisted of 397 volunteers from the Baltimore Longitudinal Study of Aging, divided into four age groups: 20-39, 40-59, 60-79, and 80 and older. The survey instrument contained 8 questions regarding the respondents' motor vehicle driving experience, followed by 18 items assessing the level of visual difficulty with various driving tasks, such as problems with oncoming headlights, seeing the instrument panel at night, judging speed, etc.

Analysis of the driving tasks component showed that age was strongly related to number and type of miles driven annually. The older drivers drove fewer miles annually, during rush hour, and at night. There was no relationship between age and driving environment (rural vs urban). A factor analysis conducted on the 18 vision-driving items revealed the following five factors: general vision/driving problems; illumination driving problems; age-related driving problems; gender; and health and education. Age loaded only with age-related driving problems. This included an age-related decline in reported visual quality, and increased level of difficulty with increasing age on eight of the visual/driving items (reading a street sign in time, seeing past dirt/rain on windshield, dim instrument panel, judging own speed, surprise when merging, other vehicles move too quickly, unexpected vehicles in the periphery, and windshield glare).

The results of this study may help to explain the types of driving problems older drivers encounter as a result of their diminishing visual capabilities. The high frequency with which older drivers report unexpected vehicles in their periphery and when they are merging is consistent with laboratory research demonstrating age-related declines in visual search for peripherally presented targets, shrinking of the visual fields, and binocular field losses, as described earlier in this section.

Finally, studies utilizing longitudinal health information on large numbers of community-living older participants have found that declining visual function is a significant factor associated with voluntary driving cessation (Marottoli, Ostfeld, Merrill, Perlman, Foley, and Cooney, 1993; Stewart, Moore, Marks, May, and Hale, 1993).

DIMINISHED COGNITIVE CAPABILITIES

Compounding the varied deficits in visual capabilities associated with increasing age, an overall slowing of mental processes has been postulated beginning as early as the fifth decade and accelerating for most individuals as they continue to age into their seventies and beyond (Cerella, 1985), and a decline has been demonstrated in a number of specific cognitive activities with high construct validity in the prediction of driving difficulties at intersections. The cognitive functions included in this processing stage perform attentional, decisional, and response selection functions crucial to safe intersection negotiation given the "tactical" and "operational" task (cf. Michon, 1979) demand levels associated with everyday operating conditions on current system facilities.

It is useful to distinguish between the generalized functional decline resulting from one of various pathological conditions which occur more frequently in the aged—most importantly the dementias—and which may predispose individuals to respond less effectively across the full range of driving tasks, versus the age-related decrements in particular cognitive functions among the normatively aging population, which can be logically or empirically related to driver behavior at intersections. The emphasis below is on the latter category of diminished capabilities, although the consequences of dementia for driving and an examination of current issues and controversy surrounding this topic are addressed at the conclusion of this discussion.

The vast literature on cognitive functions and their assessment makes a fundamental distinction that must be taken into account in the effort to focus this review on aspects of performance most relevant to intersection use by older versus younger persons. Two major categories of cognition have been defined—variously termed *crystallized* and *fluid*, or *product* and *process*—which refer, respectively, to measures reflecting the accumulated knowledge from earlier processing, and measures reflecting the efficiency of acquiring, transforming, retaining, and applying new information. In the former category, results from many studies using a wide variety of psychometric tests (e.g., vocabulary, general knowledge) show that age effects are very small, and that sometimes older persons score higher than younger persons. By comparison, measures reflecting the efficiency of current processing often show older adults to be at a disadvantage in relation to younger adults (Salthouse, 1990). The degree of age-related decline in *fluid*, or *process* cognitive functioning varies a great deal from one older individual to another, and is strongly affected by task variables.

The range of tasks performed by an older driver in the approach to and negotiation of an intersection will be addressed in detail in a subsequent section of this review. For present purposes, it may confidently be asserted that the cognitive aspects of safe intersection negotiation depend upon a host of specific functional capabilities. Most prominent among these are: (1) the access and retrieval of previously learned information to recognize and comprehend all manner of stimuli in the roadway environment, as well as the organization and integration of such information in "working memory" as required for vehicle control and navigational decisions; (2) efficient search and scanning operations, in which the most salient stimuli are discriminated from the ones that are less relevant *at that instant*; and (3) divided attention to process more deeply and respond as needed to the most salient stimuli, while allocating resources (i.e., serial, or "effortful" processing capacity) among multiple (shared) tasks.

Age Differences in Memory Functions

Memory functions are constantly coming into play as drivers must remember the route they wish to follow, the information acquired from traffic control devices as an action is initiated, and the rules for expected behavior in specific situations, at a minimum. For effective maneuvering at intersections, certain aspects of spatial (non-verbal) learning and memory may also be of particular importance. Memory is also important as a factor in other cognitive tasks, particularly "working memory," which allows the integration of continuous sensory information over time, the manipulation of information in memory for problem solving and decision making, and the division of attention between multiple, relevant sources of information such as an intersection control display and oncoming traffic. For the commonly-distinguished categories of sensory (iconic), short-term (primary), and long-term (secondary) storage, however, the operational significance of demonstrated age differences in these functions is less apparent. Pending successful registration of incoming sensory information, only gross deficits in short-term memory processes are likely to disrupt vehicle control in familiar situations where drivers can rely on crystallized knowledge to perform overlearned responses. Accordingly, this literature is briefly summarized below. The one exception in this area is "working memory," a topic addressed both in this discussion and again in the following section devoted to attentional processes, with which it is inextricably linked.

The "earliest" memory function engaged in the ongoing processing of roadway information is sensory memory, termed "iconic" memory for the visual sensory register. Research has shown that: (1) older persons do not require more time to establish a legible icon, but their icons are more susceptible to interference from distracting visual information perceived just before or just after a target stimulus (Walsh, Till, and Williams, 1978; Cerella, Poon, and Fozard, 1982); (2) the persistence or duration of icons differs with age, in that a light source can flash at a slower rate for older than for younger persons and still be perceived as a continuous (steady) signal (Kline and Schieber, 1980); and (3) the capacity of iconic memory is very large for young and old alike (Sperling, 1963).

Primary memory stores information that has been processed beyond the level of the sensory registers but which, nevertheless, is short-lived if it does not receive further attention and processing. Age-related studies of digit and letter spans suggest that there are, at best, marginal differences in the primary memory capacity of older and younger adults (Drachman and Leavitt, 1972; Parkinson, Lindholm, and Inman, 1982). Neither have significant differences between older and younger adults been observed in their respective recency effects (Craik, 1968; Smith, 1975). At least two studies investigating interference effects have measured more rapid loss of information from primary memory in older persons (Talland, 1965; Inman and Parkinson, 1983), but two earlier ones reporting no age-related differences (Kriauciunas, 1968; Keevil-Rogers and Schnore, 1969) may also be cited.

More importantly, the construct of *working memory* signifies that the primary store is a place where information is operated upon. In other words, primary memory cannot simply be construed as a repository for information; it is also the unit that performs higher level cognitive functions. Clearly, an important factor influencing the performance of these functions is the speed with which information is processed. There is now a general consensus among investigators that older adults tend to process information more slowly than younger adults, and that this slowing not only transcends the slower reaction times often observed in older adults but may, in part, explain them (Anders, Fozard, and Lillyquist, 1972; Eriksen, Hamlin, and Daye, 1973; Waugh, Thomas, and Fozard, 1978; Salthouse and Somberg, 1982; Byrd, 1984). Part of this general cognitive slowing seems to be attributed to an increase in the time it takes older adults to retrieve information from primary memory (Waugh et al., 1978; Hunt, 1978). Insofar as information in primary memory has a limited "lifespan," one would expect older adults to perform poorly on short-term memory tasks that require substantial attentional resources or on tasks that require the reorganization of to-be-remembered information. Thus, while compelling evidence does not exist to suggest that older adults differ from younger adults in either the capacity of, or the rate with which information is lost from, primary memory, older drivers will still be at greater risk in situations such as intersections that require rapid mental operations for appropriate vehicle control, especially when they are simultaneously required to perform such operations and retain other (e.g., navigational) information for future use.

Secondary memory, often labeled "long-term" memory, is generally considered to be a permanent store of unlimited capacity. Investigators of age differences in this memory function have focused on the efficiency both of encoding of information in secondary memory and of retrieval processes. Age-related decrements in the efficiency of retrieval of information from secondary memory—e.g., a deficit in recall but not in recognition memory performance—is the most common finding in the literature (Schonfield and Robertson, 1966; Hultsch, 1975; Craik, 1977; Rankin and Hyland, 1983). It should be noted, however, that the *largest* age-related differences in recall are found in intentional recall tasks, where subjects are allowed to process information in the manner of their choice (Thomas and Ruben, 1973; Eysenck, 1974; Till and Walsh, 1980; Poon, Walsh-Sweeny, and Fozard, 1980). These studies suggest that while older adults are often capable of employing strategies that promote efficient encoding, they do so far less spontaneously than do younger adults. In other words, it would appear that older subjects are relatively less able to organize material spontaneously in ways that render the material more easily remembered. Finally, three factors have been shown to minimize age-related deficits: practice (Treat, Poon, and Fozard, 1981; Howard, 1986), self-paced learning conditions (Canestrari, 1963; Hulicka and Wheeler, 1976), and familiarity (Poon and Fozard, 1978; Barrett and Wright, 1981; Hultsch and Dixon, 1983).

The relationship of secondary memory deficits among older drivers to intersection negotiation difficulties seems tenuous, at least with respect to semantic information. It is interesting to note, however, that nonverbal memory studies testing spatial and configurational variables also show older persons to be at a disadvantage relative to younger persons. It has been reported that older adults exhibit relatively slower performance and increased error rates on tasks requiring mental rotation of block drawings (Gaylord and Marsh, 1975), while other studies have found age-related deficits in accuracy but not speed of mental rotation (Herman and Bruce, 1983), or deficits in speed of mental rotation of geometric figure drawings without significant age differences in error rates (Berg, Hertzog and Hunt, 1982). Also, research using standardized tests of memory for designs (e.g., the Benton Visual Retention Test and the Wechsler Memory Scale) has shown consistent age-related declines in performance (Hulicka, 1966; Arenberg, 1978). Deficits in spatial memory are more likely to impact driving performance at intersections because navigational decisions must be acted upon at these locations. Navigational uncertainty will logically increase the likelihood of erratic maneuvers during an intersection approach; also excessive slowing—to the point where other traffic is disrupted—may characterize the behavior of a driver who is lost, as he/she processes additional cues from the environment in an attempt to retrieve sufficient spatial knowledge for a maneuver decision at the intersection. Walsh, Krauss, and Regnier (1981), in a study of the relationships between spatial ability, environmental knowledge, and environmental use by older individuals, reported that the use of services and facilities and the confidence with which trips are initiated from home are directly linked to spatial ability and spatial knowledge. There is also clinical evidence for demented populations that a disruption in spatial skills is the most common reason cited by older drivers in self-acknowledgments of diminished functional capacity (Odenheimer, 1989).

Age Differences in Attentional and Decisional Processes

The following material addresses two complementary functions that are essential to the safe and effective use of intersections, and that have been associated with significant age differences. The first involves the earliest stage of visual attention used to quickly capture and direct attention to the most salient events in a driving scene. The second involves the division of attention between targets of recognized importance to a driver, prior to a vehicle maneuver during the approach to or during the negotiation of an intersection. As commonly referenced in the technical literature, these cognitive processes are considered under the headings "selective attention" and "divided attention."

The most promising work addressing issues of selective attention and traffic safety arose, interestingly, from the general failure of earlier studies to find a reliable relationship between visual field sensitivity and motor vehicle crash experience (cf. Burg, 1968; Henderson and Burg, 1974; Waller, Gilbert, and Li, 1980). At the same time, investigators of age-related diminished capabilities, following reports of disproportionately high crash and violation rates for older drivers indicating specific problems with turning and merging maneuvers and failure-to-yield, especially at intersections (Campbell, 1966; Moore, Sedgley, and Sabey, 1982; Kline, 1986; Staplin and Lyles, 1991), noted that all these activities involve the processing of information from the peripheral visual field. Driving, however, unlike conventional visual field sensitivity tests, involves complex scenes with moving and/or distracting stimuli, plus the necessity of constantly dividing one's attention between central and peripheral vision. Thus, a preferred paradigm for conducting research in this area has emerged—the "functional" or "useful" field of view (UFOV). Measures of this field involve the detection, localization and identification of targets against complex visual backgrounds (Sanders, 1970; Verriest, Barca, Dubois-Poulsen, Houtmans, Inditsky, Johnson, Overington, Ronchi, and Villani, 1983; Verriest, Barca, Calbria, Crick, Enoch, Esterman, Friedman, Hill, Ikeda, Johnson, Overington, Ronchi, Saida, Serra, Villani, Weale, Wolbarsht, and Zinirian, 1985). UFOV is also influenced by the presence of distractors or multiple stimuli in the field of view (Drury and Clement, 1978; Sekuler and Ball, 1986; Scialfa, Kline, Lyman, and Kosnik, 1987; Ball, Beard, Roenker, Miller, and Griggs, 1988), as well as the time available to process the display (Bergen and Julesz, 1983; Ball, Roenker, and Bruni, 1990).

Most importantly, tests assessing the useful field of view appear to be better predictors of problems in driving than are standard field tests. One study examining state crash records for 53 (older) drivers who had been tested for visual/cognitive capabilities accounted for 20 percent of the variance in crash frequency with a composite predictor variable that included mental status and the size of the useful field of view; this model was much stronger than predictions based only upon visual sensory function which excluded measures of information processing at higher levels (Owsley, Ball, Sloane, Roenker, and Bruni, 1991). In this study, drivers with restrictions in UFOV had *15 times* more intersection crashes than those with normal visual attention. A following study by the same researchers examining the driving records of over 300 drivers confirmed the predictive power of UFOV. In this study, the correlation between crash frequency and useful field of view exceeded $r = 0.55$; in other words, the UFOV measure alone accounted for over 30 percent of the variance in crash experience among this study sample (Ball, Owsley, Sloane, Roenker, and Bruni, 1994).

It must be reiterated that UFOV research incorporates measures of selective attention and speed of visual information processing to arrive at an overall measure of performance. Since the UFOV measure depends upon information coming through a driver's visual sensory channel, people with serious visual loss are also likely to evidence serious impairment in UFOV. The converse is not true, however—many adults who evidence impairments in UFOV have normal visual fields. UFOV is therefore a more comprehensive measure of information processing ability than visual sensory status alone.

The relationship between UFOV and older driver performance was explored further in a simulator study conducted by Walker, Sedney, and Mast (1992). The age-related narrowing of the UFOV was examined in this research using dynamic vehicle targets presented in realistic contexts on large-screen video systems, as opposed to the smaller CRT test monitor used by the applied vision researchers most active in developing this paradigm. A central tracking task of varying difficulty simulated the control tasks of driving, while vehicle images were introduced on the left and right periphery, and on a screen to the rear of the subject. Results indicated significant slowing of older (ages 65-70) drivers' responses to peripheral targets as the effort required to perform the forward tracking task was increased, while no effect of central task loading was obtained for young (ages 20-25) and middle-aged (ages 40-45) drivers. Age differences in simple reaction time (RT) as an explanation of these results was subsequently ruled out, supporting the interpretation of significant narrowing of the UFOV with age in a test protocol more closely representing the visual cues present during actual driving. The study authors, noting the strong predictive relationships between UFOV and intersection crash involvement found in the literature (see Ball and Owsley, 1991), suggest that reduced UFOV may contribute to the "looked, but didn't see" crash category. It is interesting to note that older drivers experience roughly the same proportion of lane-changing crashes as drivers in other age groups, but individuals over the age of 70 are twice as likely to be cited as at fault in this crash type (Monforton, Dumala, Yanik, and Richter, 1988).

As the UFOV paradigm has attracted increasing attention as a potential predictor of traffic safety outcomes, other investigations of age-related differences in this functional capability have yielded more equivocal results. Perry, Koppa, Huchingson, Ellis, and Pendleton (1993) have reported a study using performance on a "brief field of view" (BFOV) measure—a closely related technique for measuring a subject's ability to obtain information from the center of a briefly presented array while simultaneously detecting a peripheral target—to predict performance in controlled field studies of traffic signal detection at systematically varying degrees of eccentricity from the driver's forward line of sight. The controlled field study conditions simulated an intersection with a three-lane approach; drivers reported briefly presented traffic signal configurations (a different color in each lane) while they were driving toward the signal array. In the laboratory, the older drivers in this study did not differ from younger subjects in their ability to process information in the central 5° area of focus, but had greater difficulty acquiring data from portions of the visual field distal to the center. The results of Perry et al. (1993) parallel those of others in this respect (cf. Owsley et al., 1991). However, Perry et al. (1993) did *not* find a significant correlation between the laboratory BFOV measure and signal identification performance under the controlled field conditions for older drivers in this study. The authors suggest that inclusion of a skilled motor task (driving) in the field test could be an important issue, such that older drivers' relative differences in maneuvering skill/motor performance could have differentially reduced their processing capacity available for the perceptual (signal identification) task.

Brown, Greaney, Mitchel, and Lee (1993) employed the UFOV testing protocol of Ball, Roenker, Bruni, Owsley, Sloane, Ball, and O'Connor (1991) to measure visual attention capabilities of a group of 1,475 ITT Hartford insurance policyholders ranging in age from 50 to 80 and above. These individuals were divided into two groups, according to the presence or absence of recent at-fault crashes on their driving records, and the researchers tested for significant correlations between crash status and each of a number of measures from a psychophysical test battery (including UFOV). The obtained correlation for UFOV and at-fault crashes was 0.05, characterized by the authors as "unexpectedly low," though statistically significant. It should be noted that the older drivers participating in this study were volunteers, raising questions about selection bias toward the most capable members of this cohort. Also, a noisy, crowded test environment was described which may have yielded unrepresentative visual attention measures.

The importance of selective attention and attention switching to the safe performance of older drivers has also been argued by Parasuraman and Nestor (1991). These researchers cite the application of dichotic listening measures to demonstrate impairments in the ability of mild and moderate Alzheimer's patients to disengage or reorient attention, while their ability to initially adopt a focused attention state remained unaffected (Greenwood, Parasuraman, and Haxby, 1989, 1991). To the extent that a driver's approach to and negotiation of an intersection is an effortful, capacity-demanding processing task involving the continuous monitoring of competing external stimuli as well as internal vehicle controls/displays, a loss of efficiency in attention switching has at least a high construct validity as a predictor of crash likelihood. Further, a recent meta-analytic study of predictors of driving crash involvement (Arthur, Barrett, and Alexander, 1991) found (auditory) selective attention to be the most valid predictor.

Drivers' difficulties in the negotiation of intersections also should reflect the *divided* attention demands they face in such situations. Given the concurrent demands for lane selection, and vehicle control for path maintenance, plus vigilance for potential conflicts with other vehicles and pedestrians, it is important to highlight recent efforts to measure age differences in this critical cognitive activity.

Of particular interest is the research program underway at the Traffic Research Centre in The Netherlands, including driving simulation studies with two continuous performance tasks—a compensatory lane-tracking task and a (self-paced) visual choice reaction time task. Researchers in this laboratory took the important step of controlling for impairments already present at the single-task level. That is, single task difficulty was adjusted to stable and equivalent levels for younger and older subjects before initiating experiments on allocation-of-resources effects under divided-attention conditions. One notable experiment was conducted by Ponds, Brouwer, and van Wolffelaar (1988). For their tracking task, in which subjects used the steering wheel to compensate for "sidewinds" that pushed the vehicle away from a straight-ahead heading, a time-on-target (TOT) score was the dependent measure, defined as the time the subject's car was wholly within its lane boundaries. For the visual reaction time task, subjects had to count the number of dots in a randomly generated array superimposed within a predefined rectangular area in their forward field of view; either 9 dots out of 40 possible locations were filled in (50 percent of cases) or 8 or 10 dots (25 percent of cases each) on a trial, with counting accuracy as the dependent variable on this self-paced task. A new dot array was presented as soon as the subject had performed a "9" versus "not 9" choice to the previous array, separated by a 500 milliseconds visual masking stimulus. Subjects' resource allocation between the two tasks was governed by verbal instructions within separate blocks of test trials, according to five different strategies: concentrate solely on tracking, emphasize tracking, give equal attention to tracking and dot counting, emphasize dot counting, and concentrate solely on dot counting.

The Ponds et al. (1988) study constructed performance-operating-characteristic (POC) curves based on the results obtained under each resource allocation strategy, where performance in one task is plotted as a function of performance on the other task, for each block of test trials. Differences between POCs thus represent differences in divided attention ability. This analysis revealed a clear decline in dual task performance for older (mean age = 68.6) versus younger (mean age = 27.5) and middle-aged (mean age = 46.7) subjects, manifested principally through larger performance decrements on the tracking task. This outcome is explained in part as reflecting the self-paced nature of the visual choice task. Assuming that both of these adaptive, continuous tasks compete for the same attentional resources (cf. Wickens, 1984), these results are important in establishing an empirical basis for the reports of exaggerated difficulties for older drivers in divided attention conditions, and particularly at intersections.

A follow-on study by Brouwer, Waterink, van Wolffelaar, and Rothengatter (1991) sought the locus of the divided attentional impairment reported above. Since the response mode for the visual discrimination task was a button-push, and since it has been documented that aging particularly affects the integration of motor skills (Korteling, 1991), Brouwer et al. (1991) replicated the earlier work using an additional, vocal response mode for this task. The tracking task remained as described above. Using correct dot counts and time on target measures, as noted earlier, these researchers again plotted POC curves. Divided attention deficits for older subjects due principally to tracking task impairments were again indicated, and differences between young and old subjects were larger when they responded manually (button-push) on the dot-counting task than when they responded vocally (though vocal responding led to more errors). This finding supported the hypothesis that response integration may play a significant role in age-related divided attention deficits associated with performance of (simulated) driving tasks.

Finally, Brouwer, Ickenroth, Ponds, and van Wolffelaar (1990) varied this research methodology such that the dot array in the self-paced visual choice task was presented peripherally as well as in the driver's central field of view. This study was prompted by the observation that their initial effort left out one key component of divided attention demands under actual driving conditions: active visual search for information at unpredictable locations. According to other investigators (Plude and Hoyer, 1985), and as documented earlier in this review, the efficiency of visual search processes is especially age-sensitive. Brouwer et al. (1990) found that varying the resource allocation strategy (via instructions) did not influence older drivers on the dot-counting task for centrally-presented patterns, but had a significant effect for peripheral stimuli. The shifting allocation strategies presumably affected the extent of active visual search (i.e., involving eye movements). This finding suggests that if drivers must increase their attention to—for example—an unfamiliar roadway feature downstream to make appropriate maneuver decisions during an intersection approach, an impairment in the discrimination of peripheral targets is likely.

Another perspective on this problem is provided by attempts to measure the mental workload imposed upon vehicle operators under varying traffic conditions. As attentional demands for varying driving tasks shift according to situation, increase in task loading may produce few or no measurable increases in error rates as the operator allocates more resources to the task in question. At some point, when all available resources are allocated, a sharp increase in errors results from further task loading. At low levels of load, an individual's resources not committed to a task represent "spare capacity." In describing age differences in attentional ability related to safe performance at intersections, it would clearly be useful to establish the level of demand that can be met before the "break point" in error rate occurs. By requiring the operator to perform a subsidiary task that utilizes unallocated attentional resources, estimates of both spare capacity and primary task load can be derived. A field study of subsidiary task measures in driver loading is noteworthy in this regard (Zeitlin, 1993).

The Zeitlin (1993) study built upon earlier work (Zeitlin and Finkelman, 1975) indicating delayed digit recall and random digit generation, using oral responses, to be appropriate subsidiary tasks for driver workload measurement, according to these criteria: (1) minimal interaction with the primary task; (2) greater performance degradation as a function of decreased capacity than the primary task; and (3) monotonic or predictable changes in performance as a function of spare capacity. Data reported by Zeitlin (1993) were collected over a 4-year period for van pool drivers commuting from upstate New York to New York City while traversing a mix of rural secondary roads, limited access highways and expressways, urban arterials, and city streets. During a 2-minute test period on both inbound and outbound commutes, subjects performed each subsidiary task under conditions of varying primary task difficulty. The primary driving task difficulty was gauged in terms of speed and traffic density, the frequency of brake applications by the driver, and subjective ratings of driving difficulty. A workload index calculated by dividing the number of brake actuations by the square root of speed—a composite measure of steady state and transient driving conditions—was correlated highly (r = 0.834) with errors on the digit recall task. In addition, the digit recall task correlated highly (r = 0.615) with rated driving difficulty. This convergence supported the author's assertion that the digit recall subsidiary task can provide a good measure of spare capacity and can be used to infer primary task workload.

While the study reported by Zeitlin (1993) did not examine age differences, specifically, it deserves mention in this review because of the indicated sensitivity of the working memory measure (delayed digit recall) to concurrent attentional demand *under actual driving conditions*. The construct of working memory (cf. Salthouse, 1990), which incorporates the allocation and control of attentional capacities (Baddeley, 1986), is a dominant theoretical framework guiding research on age differences in cognition. Baddeley (1986) has characterized working memory as "a system for the temporary holding and manipulation of information during the performance of a range of cognitive tasks." An age-related limitation in the information processing capability of working memory is the central tenet of much of the work which demonstrates a decline by older subjects on cognitive tasks, including the selective attention and divided attention processes cited above as crucial to safe intersection negotiation.

Finally, decisional processes drawing upon working memory crucial to safe performance at intersections may be illustrated through a study of alternative strategies for presentation of left-turn traffic control messages (Staplin and Fisk, 1991). This study evaluated the effect of providing advance left-turn information to drivers who must decide whether or not they have the right-of-way to proceed with a protected turn at an intersection. Younger (mean age 37) and older (mean age 71) drivers were tested using slide animation to simulate dynamic approaches to intersection traffic control displays, with and without advanced cueing of the "decision rule" (e.g., LEFT TURN MUST YIELD ON GREEN ●) during the intersection approach. Without advanced cueing, the decision rule was presented only on a sign mounted on the signal arm across the intersection *as per* standard practice, and thus was not legible until the driver actually reached the decision point for the turning maneuver. Cueing drivers with advanced notice of the decision rule through a redundant upstream posting of sign elements significantly improved both the accuracy and latency of all drivers' decisions for a "go/no go" response upon reaching the intersection, and was of particular benefit to the older test subjects. Presumably, the benefit of upstream "priming" is derived from a reduction in the requirements for serial processing of concurrent information sources (sign message and signal condition) at the instant a maneuver decision must be completed and an action performed. The differences in maneuver decision responses demonstrated in this study illustrate both the potential problems older drivers may experience at intersections due to working memory deficits, and the possibility that such consequences of normal aging can to some extent be ameliorated through improved engineering design practices.

Older Drivers' Self-Perceptions of Declining Cognitive Skills

Drivers participating in the Gutman and Milstein (1988) focus group study were asked to report what they were most concerned about with respect to their driving ability. Across all age groups, the biggest fear was loss of attention/concentration. This fear was reported by 30 percent of the drivers age 76 and older, 26 percent of those ages 66 to 75, and 24 percent of those ages 56 to 65. The majority of these drivers (41 percent across all age groups) believed that older driver inattention was the primary reason for crashes involving older drivers. Over one-half (55.6 percent) of the drivers age 76 and older stated that older drivers' crashes are a result of reduced attentiveness, compared to 37 percent of drivers ages 66 to 75, and 39.5 percent of drivers ages 56 to 65. Older drivers' misjudgment of other vehicles and drivers was cited as causing crashes by 7 percent of the participants, across all age groups.

In the Kline et al. (1992) survey described earlier, the older participants reported greater difficulty judging both the speed of their vehicle as well as that of other vehicles, and expressed a concern over other vehicles "moving too quickly." This perceived difficulty is consistent with increased proportions of turning crashes and right-of-way violations for this group. The older drivers' perceptual/cognitive difficulties in judging vehicle speeds is in agreement with research describing older drivers' deficits in motion detection and "least safe gap" judgments, as discussed earlier.

DIMINISHED PHYSICAL/PSYCHOMOTOR CAPABILITIES

Contemporary views on the effects of age on body movements as they relate to driving behavior clearly distinguish between the complementary processes of *response initiation* and *movement time* (see Stelmach and Nahom, 1992). Response initiation, in turn, is presumed to reflect capabilities in the areas of response preparation, response selection, and response programming, and is sensitive to changes in task complexity and requirements for speed versus accuracy of response. Measures of movement execution, by comparison, address individual and group differences in movement trajectories and kinematics, kinetics (muscular force), coordination, joint flexibility, and sensory-motor integration. Prior studies have been consistently characterized by cross-sectional research designs, and, as elaborated below, have consistently indicated that there is age-associated slowing in motor performance, across all component processes. Questions remain, however, as to the aspect(s) of psychomotor capability which account for the greatest variance in the overall accuracy or latency measures of driver response.

It has been hypothesized by Salthouse (1985) that nearly all cognitive motor processes are slowed by approximately the same proportional amount with increasing age. The stages of response selection and response programming may be particularly sensitive to age-related decline, however. Response selection represents the output stage of sensory/perceptual and cognitive processing of information from the roadway environment, up to and including decision-making. Given the dynamic nature of the driving task, individuals are *continuously* engaged in the discrimination of "most relevant" stimuli, and subsequent initiation of a best—or at least an adequate—vehicle control response.

Investigations of response selection compare reaction times (RTs) as the number of response alternatives, or level of uncertainty, increases. In simple RT tasks, only slight age differences are commonly obtained (Gottsdanker, 1982). This type of study may generally be characterized as one in which a substantially suprathreshold and unambiguous signal and a well-learned response are both known in advance of a test trial. In contrast, using a choice RT paradigm, many researchers have determined that older adults are significantly slower than younger adults when response uncertainty is increased, indicating a disproportionately heightened degree of risk for older drivers when faced with two or more choices of action (Simon and Pouraghabagher, 1978; Vegega, 1989).

Tarawneh (1991) examined findings published by proponents of both "parallel" and "sequential" (serial) models of driver information processing, seeking to determine the best estimator for older individuals of a perception-reaction time (PRT) encompassing six different component processing operations for determining traffic signal change intervals: (1) latency time (onset of stimulus to beginning of eye movement toward signal); (2) eye/head movement time to fixate on the signal; (3) fixation time to get enough information to identify the stimulus; (4) recognition time (interpret signal display in terms of possible courses of action); (5) decision time to select the best response in the situation; and (6) limb movement time to accomplish the appropriate steering and brake/accelerator movements.

Tarawneh's (1991) review produced several conclusions. First, the situation of a signal change at an intersection is among the most extreme, in terms of both the information-processing demand and subjective feelings of stress that will be experienced by many older drivers. Second, the most reasonable interpretation of research to date indicates that the best "mental model" to describe and predict how drivers respond in this context includes a mix of concurrent and serial-and-contingent information-processing operations. In this approach, the most valid PRT estimator will fall between the bounds of values derived from the competing models thus far, also taking age-related response slowing for recognition, decision making, and limb movement into account. Tarawneh indicated the need to increase design values—relative to those derived from studies of young drivers—by 5 to 45 percent for the stimulus recognition phase, 20 to 100 percent for response decision, and 20 to 90 percent for limb movement, to accommodate 95 percent of the older driver population. (The net increase in the design standard for signal change time recommended by this author was from 1.0 to 1.5 seconds.)

A contrasting set of results was obtained in a recent FHWA-sponsored study of traffic operations control for older drivers (Knoblauch, Nitzburg, Reinfurt, Council, Zegeer, and Popkin, 1995). This study compared the decision/response times and deceleration characteristics of older drivers (ages 60–71+) with those of younger drivers (under age 60) at the onset of the amber signal phase.

Results of the Knoblauch et al. (1995) study showed no significant differences in 85th percentile decision/response times between younger and older drivers when subjects were close to the signal. When subjects were further from the signal at amber onset, older drivers had significantly longer decision/response times than the younger drivers. The authors suggested that the significant differences between older and younger drivers occurred when the subjects were relatively far from the signal, and that some older subjects will take longer to react and respond when additional time is available for them to do so. Thus, they concluded that the older drivers were not necessarily reacting inappropriately to the signal. In terms of deceleration rates, there were no significant differences, either in the mean or 15th percentile values, between the older and younger subjects. Together, these findings led the authors to conclude that no changes in amber signal phase timing are required to accommodate older drivers.

A study by Stelmach, Goggin, and Garcia-Colera (1987) examined response preparation where the independent variables were pretrial information level (complete, partial, or none) concerning which arm to move, the direction of movement, and the extent of movement. They demonstrated a significant and disproportionate slowing of response for older (ages 60-65) versus both young (ages 18-25) and middle-aged (ages 40-47) adults as uncertainty level increased. Based on related work, Goggin, Stelmach, and Amrhein (1989) concluded that preparatory intervals and length of precue viewing times appear to be crucial determinants of age-related differences in movement preparation and planning. When older adults are permitted to have longer stimulus exposures and longer interstimulus intervals, they exhibit less slowing of movement (Eisdorfer, 1975; Goggin et al., 1989). The spacing of vehicle control movements required of drivers to negotiate intersections therefore may be expected to strongly influence the ability of older individuals to respond in a safe and timely manner. In this regard, intersections that require weaving or successive lane changes within a restricted timeframe—as often found, for example, in dual left-turn lane geometries, or where a lane change to merge with traffic from an acceleration lane is required after negotiating an auxiliary right-turn lane with a channelizing island—should be the most difficult for this user group.

The "programming" of driver responses is a closely related issue. Stelmach, Goggin, and Amrhein (1988) predicted that older adults would have greater difficulty in situations in which anticipated driving actions must be altered. Subjects received pretrial information about the type of movement which was to occur following a cue. Accurate pretrial information (80 percent probability) defined a "planning" condition, and inaccurate information (20 percent probability) defined a "restructuring" condition in this experiment. As expected, older subjects were slower to initiate a response than younger subjects, and particularly when performing under the restructuring condition. These researchers conclude that older drivers will have greater difficulty in situations in which anticipated driving actions must be rapidly altered. The previously noted facilitation by Staplin and Fisk (1991) of maneuver decisions and hence, response selection during intersection left turn approaches by "priming" the driver with redundant upstream signing further underscores this age difference.

A related measurement of physical response capability was undertaken by Staplin, Lococo, and Sim (1990) in an experiment examining cumulative latencies for brake, accelerator, and steering wheel responses in a driving simulator. Three conditions were tested: (1) a baseline condition, where only a single control response was required; (2) a two-movement response sequence; (3) and a three-movement response sequence. The various permutations of response types within each sequence were tested (e.g., accelerate-brake-steer), with right- and left-steering responses equally distributed across trials. Slides with simple icons (red ball, green ball, and right- and left-pointing blue arrows) cued the subjects to make specific control movement sequences on a given trial. The slides were presented for a 400 millisecond (ms) duration with a 50 ms interstimulus interval, at a common fixation point. Results showed an advantage for younger subjects in performing a single control response that was very small, while the relative decrement for older subjects in speed of response widened progressively as the required control movement sequences included two and three reactions. These data were interpreted as an indication that older drivers will be at relatively greater risk than younger or middle-aged drivers when they must override a just-initiated vehicle control movement with one or more successive movements. Again, the need to avoid geometric designs which increase the likelihood that older drivers will be called upon to execute multiple responses in rapid succession is emphasized.

The movement execution factors contributing to response slowing in older adults, apart from the issues of response selection, programming, and preparedness so important to movement initiation, is relatively more straightforward. A review by Welford (1984) indicates that movement time—the interval between the initiation of movement and its completion—is significantly slower among the older population than among the young. Age-related motor impairments have been linked to decreases in muscle mass and elasticity, decreases in bone mass, and a reduction of central and peripheral nerve fibers (Welford, 1982). Muscular atrophy and related neural losses during aging are known to disproportionately affect the ability to control movement rapidly and accurately (Larsson, Grimby, and Karlson, 1979). Goggin and Stelmach (1990) reported findings which show that muscular force control may be impaired in older adults, with the result that movement corrections during movement execution are slower and much less efficient. In addition, the synchronous activation of muscles on one side of the body versus the other, as well as the inhibition of inappropriate postural responses, has been shown to be more difficult for older than for younger adults (Stelmach, Phillips, DiFabio and Teasdale, 1989). These findings suggest that older individuals may have a diminished capability to perform coordinated voluntary movements as required on a continual basis for safe and effective vehicle control.

Finally, the slowing of psychomotor responses of older drivers reflects a decline in head and neck mobility, which accompanies advancing age. Joint flexibility, which is an essential component of driving skill, has been estimated to decline by approximately 25 percent in older adults (Smith and Sethi, 1975), due to arthritis, calcification of cartilage, and joint deterioration. This restricted range of motion reduces an older driver's ability to effectively scan to the rear and sides of his/her vehicle to observe blind spots, and similarly may be expected to hinder the timely recognition of conflicts during turning and merging maneuvers at intersections (see Ostrow, Shaffron, and McPherson, 1992). Of respondents to an older driver survey conducted by Yee (1985), 35 percent reported problems with arthritis and 21 percent indicated difficulty in turning their heads to scan rearward while driving.

The practical consequences of restricted head and neck movement on driving performance at T-intersections were investigated by Hunter-Zaworski (1990), using a simulator to present videorecorded scenes of intersections with various levels of traffic volume and sight distance in a 180° field of view from the driver's perspective. Two subject groups, drivers ages 30-50 and drivers ages 60-80, depressed a brake pedal to watch a video presentation (on three screens), then released the pedal when they judged that it was safe to make a left turn; half of *each* age group had a restricted range of neck movement as determined by goniometric measures of maximum (static) head turn angle. Aside from demonstrating that skewed intersections are hazardous for any driver with an impairment in neck movement, this study found that maneuver decision time increased with both age *and* level of impairment. Thus, the younger drivers in this study were able to compensate for their impairments, but older drivers both with and without impairments were unable to make compensations in their (simulated) intersection response selections.

One encouraging note is that many of the movement execution problems associated with losses in flexibility pervasive among older road users may stem simply from an overall decline in physical fitness among this group, and is thus amenable to remediation. One research study involving 63 older drivers found that drivers ages 60-75 demonstrated less shoulder flexibility and torso/neck rotation than a comparison group including 43 younger drivers (McPherson, Ostrow, and Shaffron, 1988). However, an exercise program conducted by Ostrow et al. (1992) was shown to be an effective intervention for older drivers for enhancing driving skills that accentuate demands on the range of motion, such as observing to the rear and parallel parking. The exercises consisted of chin flexion/extension, neck rotations, head side bending, chin tucks, rotating the shoulders backward, and trunk rotations. After participating in the program, older drivers showed improvements using a field-based assessment of automotive driving skill. Subjects in the experimental group who received the range-of-motion training looked more frequently to the sides and rear of their vehicle than drivers in a control group who did not participate in the exercise program.

Older Drivers' Self-Perceptions of Declining Physical Skills

Difficulty with head turning and fatigue were reported as impairments that make driving difficult by approximately 17 percent of the participants in the Gutman and Milstein (1988) focus group study. Thirty-seven percent of the 162 participants believed that older drivers were involved in crashes as a result of their slowed reactions. This response was more frequent for drivers age 76 and older (52 percent), compared to drivers ages 66-75 (30 percent), and drivers ages 56 to 65 (37 percent). It should be noted that subjects contributed multiple responses to this question. More drivers age 76 and older attributed older driver crash involvement to physical impairments (11 percent) and driving beyond one's capabilities (11 percent) than drivers ages 56-65 and 66-75. Excluding vision/visibility problems associated with nighttime operations, difficulty with head turning placed first among *all* concerns mentioned by older drivers in a focus group conducted by Staplin, Harkey, Lococo, and Tarawneh (1997) to examine problems in the use of intersections where the approach leg meets the main road at a skewed angle, and/or where channelized right turn lanes require an exaggerated degree of head/neck rotation to check for traffic conflicts before merging.

Physical problems have been associated with voluntary driving cessation by older community-living individuals. Marottoli et al. (1993) found particularly that Parkinson's Disease, stroke, arthritis, hip fractures, inability to perform one or more basic activities of daily living (ADL) or Rosow-Breslau items (climbing stairs, walking one-half mile, heavy house work), and lack of participation in physical activities (active sports, physical exercises, gardening and walking) were significantly associated with driving cessation. Similarly, the Stewart et al. (1993) study included stroke, hospitalization in the past year, and Parkinson's Disease as significant predictors of the likelihood of driving cessation.

DEMENTIA AND DIMINISHED DRIVING SKILLS

As documented above, there are numerous functional changes that occur with normal aging that may impact on safe driving: impaired visual sensitivity, reduced selective attention and slowed reaction time, for example. However, a number of diseases commonly occurring among older persons may result in even more serious driving difficulties. These diseases largely affect vision, hearing, mood, motor function, joint mobility, level of consciousness and other cognitive functions. These conditions are also typically associated with the use of multiple medications which further complicate the problem. We have an inadequate understanding of how each functional/medical problem specifically impacts on driving safety. We are even further in the dark in terms of co-morbidity, that is when a number of these conditions co-exist. The disorders that affect cognitive function are of particular concern, since they are often insidious and easily missed by licensing agencies and even by health care providers.

The syndrome most often identified in older individuals with progressive loss of cognitive function is called "Dementia." Although the term is not always used in a uniform way, the most widely accepted definition for this disorder is characterized by the American Psychiatric Association in its *Diagnostic and Statistical Manual, 3rd Edition-Revised (DSM III-R)*. The key elements from the *DSM III-R* required for a diagnosis of Dementia, as well as the elements required to identify other relevant conditions in the older population that could impact on driving, are listed in Table 2. The paragraphs immediately following expand upon line items from the *DSM III-R* to provide brief descriptions of the terms and types of difficulties that might be expected in a person with features of dementia or related problems.

"Memory impairment" refers to the inability to learn new information. This has ramifications in particular when there are changes in familiar environments, such as detour or speed limit signs. It may also affect the ability of a person to retain information from a complex sign such as "NO LEFT TURN BETWEEN 7-9 AM ON WEEKDAYS."

Impaired abstract thinking refers to the ability to understand how symbols such as picture signs relate to actual driving behavior. It also is associated with difficulty switching from one task to another such as required when dealing with complex traffic situations (e.g., intersections).

Impaired judgment refers to the inability to make correct decisions, such as when it is safe to turn across the intersection. Although this function is difficult to measure in the clinical setting, it may be one of the most relevant of disturbances for the demented driver.

Table 2. Definitions adapted from DSM III-R.

DEMENTIA

A. Memory impairment.
B. At least one of the following:
  1. Impairment of abstract thinking.
  2. Impaired judgment.
  3. Other disturbances of higher cortical functions.
  4. Personality change.
C. The disturbances in A and B interfere with work, social activities or relationships.
D. Not occurring exclusively during the course of Delirium.
E. Either: 1 or 2
  1. Evidence from the history, exam or tests, of a specific etiology.
  2. In the absence of such evidence, other diagnoses reasonably excluded.

PRIMARY DEGENERATIVE DEMENTIA

A. Diagnosis of Dementia.
B. Insidious onset with generally progressive deteriorating course.
C. Exclusion of all other causes of Dementia by the history, exam, and tests.

MULTI-INFARCT DEMENTIA

A. Diagnosis of Dementia.
B. Stepwise deteriorating course with "patchy" distribution of deficits early in the course.
C. Focal neurological signs and symptoms.
D. Evidence from history, exam, or tests, of significant cerebrovascular disease.

DELIRIUM

A. Reduced ability to maintain attention and to shift attention to external stimuli.
B. Disorganized thinking, with speech that may be incoherent.
C. At least two of the following:
  1. Reduced level of consciousness.
  2. Perceptual disturbance: misinterpretations, illusions, or hallucinations.
  3. Disturbance of sleep-wake cycle.
  4. Increased or decreased psychomotor activity.
  5. Disorientation to time, place or person.
  6. Memory impairment.
D. Develops over hours to days and fluctuates over the course of a day.
E. Either 1 or 2
  1. Evidence from the history, physical exam, or lab tests, of a specific etiology.
  2. Disturbance cannot be accounted for by a non-organic mental disorder.

AMNESTIC SYNDROME

A. Memory impairment.
B. Not occurring exclusively during the course of Delirium and isn't Dementia.
C. Evidence from the history, physical exam, or laboratory tests, of a specific etiology.

MAJOR DEPRESSION

A. At least 5 of below ("Depression/ SIG: E CAPS")
  1. Depressed mood
  2. Sleep increased or decreased
  3. Interest decreased (hobbies/sex)
  4. Guilt (worthlessness)
  5. Energy decreased (fatigue)
  6. Concentration decreased
  7. Appetite/weight increased or decreased
  8. Psychomotor retardation or agitation
  9. Suicidal ideation/recurrent thoughts of death
B.
  1. No organic etiology identified
  2. Not uncomplicated bereavement.
C. No delusions or hallucinations in the absence of mood symptoms.
D. Not superimposed on Schizophrenia, Delusional disorder, or Psychotic disorder.

Higher cortical functions refer to the ability of the brain to interpret visual, auditory or tactile information accurately. That is, when one loses the ability to understand language, then signs with words may become meaningless. When one loses the ability to see the environment in a structured way, then the relationships between the streets, the cars and the signals may become distorted and driving is likely to become extremely dangerous.

Personality changes are also very important since they are often associated with impulsivity in behaviors such as impatience in traffic and at busy intersections. Impulsivity can lead to dangerous behaviors, such as prematurely pulling out into traffic or running a red light.

"Primary Degenerative Dementia" most often refers to Alzheimer's Disease. It is based on a diagnosis of dementia in the setting of a slowly progressive course of deterioration. In contrast, "Multi-Infarct Dementia" also begins with a diagnosis of dementia but is distinguished from Alzheimer's Disease by a course classically typified by a series of strokes.

Delirium is also a very common problem in the older population. It is often caused by one or more medications. It can look a lot like dementia except it tends to begin more rapidly and is typified by distractibility or inattention. It is reasonable to believe that if one is inattentive while driving that critical information needed to maneuver in traffic will be missed. Other features of delirium are even more ominous: a reduced level of consciousness which refers to the degree of alertness or difficulty staying awake; and perceptual disturbances, which refer to misinterpretation of what is perceived or imagining things that do not exist.

In addition to poor concentration and motivation, the symptoms presented by patients with depression may include memory impairments. Other disorders that commonly affect cognition in older individuals are strokes, Parkinson's Disease, diabetes, and cardiac arrhythmias (American Psychiatric Association, 1987).

The most troubling of the dementias is Alzheimer's Disease (AD). Alzheimer's Disease is the most common cause of dementia, with a prevalence—based on correlation between autopsy data and the outcomes of strict clinical diagnostic procedures—estimated to be as high as 11.6 percent for those 65 and older and 47.8 percent for those over the age of 85 (Evans, Funkenstein, Albert, Scheer, Cook, Herbert, Hennekens, and Taylor, 1989). Alzheimer's Disease typically is characterized by decline in memory, judgment, personality, and/or some other cognitive dysfunction (such as language or visual perceptual skills) (American Psychiatric Association, 1987). Most often, deficits seen in dementing disorders are not isolated, but coexist in variable combinations of decline in memory, language, visuospatial, and executive functions.

There is no simple test to diagnose Alzheimer's Disease; however, there are strict standards used in research settings, as presented in Table 3. These were developed by the National Institutes of Neurologic and Communicative Disorders and Stroke and the Alzheimer's and Related Disorders Association (NINCDS-ADRDA) (McKhann, Drachman, Folstein, Katzman, Price, and Stadlan, 1984).

The trigger that starts the symptoms of Alzheimer's Disease is unknown. We do know that it sometimes runs in families, and that cells deep in the center of the brain (Nucleus Basalis of Meynert) eventually lose the ability to make chemicals needed for communication between selective parts of the brain. The most important of such deficits is the inability to manufacture acetylcholine, which is particularly important in the parts of the brain that interpret sensory information. That is why as the disease progresses, the victims of Alzheimer's Disease have increasing difficulty in *comprehending* what they see, hear, and feel, even though they continue to see and hear and feel.

Table 3. Criteria for clinical diagnosis of Alzheimer's Disease (Adapted from the NINCDS-ADRDA).

A. The clinical picture must be compatible with the DSM III R definition of dementia.

B. The diagnosis of "probable" Alzheimer's Disease is characterized by:
1. Clinical impression of dementia is supported by neuropsychological tests.
2. Deficits in 2 or more areas of cognition.
3. Progressive worsening of memory and other cognitive functions.
4. No disturbance of consciousness.
5. Onset between 40 and 90 years of age.
6. Absence of systemic disorders or other brain diseases that could account for the progressive deficits in memory and cognition.

C. The diagnosis is supported by:
1. Progressive aphasia, apraxia, agnosia (inability to interpret what is seen, heard or felt)
2. Impaired ADLs (ability to care for oneself) and change in behavior.
3. Family history of similar disorder especially if pathologically confirmed.
4. Normal spinal fluid, normal or non-specific slowing on EEG, atrophy on CT with evidence of progression by serial studies.

D. Other features consistent with the diagnosis:
1. Plateaus in the course.
2. Depression, insomnia, incontinence, delusions, illusions, hallucinations, catastrophic outbursts, sexual disorders, and weight loss.
3. Increased muscle tone, myoclonus or gait disorder in advanced disease.
4. Seizures in advanced disease.
5. Normal CT.

E. Features that make the diagnosis unlikely:
1. Sudden onset.
2. Focal neurologic signs early in the course.
3. Seizures or gait problems early in the course.

Driving problems may be an early sign of dementia, because of the great demands for selective attention, judgment, and visual interpretation. Demented drivers may become lost in familiar areas; they may become confused by detours or heavy traffic; they may misinterpret signs and signals; or they may accelerate when they intend to brake (Kaszniak, Keyl, and Albert, 1991).

Demented drivers are at increased risk for crashes especially in the advanced stages of their disease (Waller, 1967; Friedland, Koss, Kumar, Gaine, Metzler, Haxby, and Moore, 1988; Lucas-Blaustein, Filipp, Dungan, and Tune, 1988; Drachman and Swearer, 1993). In a questionnaire survey of 130 Alzheimer's Disease (AD) patients and 112 age-matched, nondemented control subjects, Drachman and Swearer (1993) found that for all years of driving following the onset of dementia, AD patients had a mean of 0.091 reported crashes per year compared with 0.040 reported crashes per year for controls in the same time period. Although the AD patients had slightly twice as many reported crashes per year as the controls, this rate is less than the average of 0.148 reported crashes per year for registered 16- to 24-year-old males. The average number of crashes per year changed with each year of driving following the onset of AD, with considerably lower reported crash rates during the initial years of dementia. In year one, the crash rate was 0.068; in year two, 0.097; in year three, 0.093; in year four, 0.159; and in year five and beyond, 0.129. For comparison, registered drivers of all ages have an average of 0.067 reported crashes per year, while registered drivers age 65 and older have an annual average of 0.037 reported crashes. When the data for the first three years post-AD are combined, the crash rate is 0.072. The AD patients incurred their first crash an average of 2.20 years post-AD. Thus, this study indicates that throughout the first three years the crash rate for AD patients is only slightly higher than that for drivers of all ages in the United States, and remains well below that of young adults aged 16 to 24. Although the course of AD may vary considerably, these findings suggest that the increase in crash risk develops toward the end of the third year, and more than doubles in the fourth year. Drachman and Swearer (1993) therefore suggest that patients who have had AD for more than two years should have their driving ability closely monitored if they are to continue driving, as the overall risk to society during the first two years is well within the accepted range for other drivers. They also note that mental status evaluations may be useful in identifying older drivers who are beginning to show evidence of cognitive decline, but on-road or off-road tests, especially those requiring the driver to follow sequential directions, are more likely to measure the skills required for driving.

Research relating driving cessation to the onset of Alzheimer's Disease is equivocal. There are a number of studies which suggest that patients with Alzheimer's Disease tend to drive until a crash occurs (Shemon and Christensen, 1989; Carr et al.,1990; Logsdon and Teri, 1990; Gilley, Wilson, Bennett, Stebbins, Bernard, Whalen, and Fox, 1991; and O'Neill, 1992). Additional research indicates that some drivers with Alzheimer's Disease engage in self-regulation, and still others cease driving altogether. Carr, Jackson, and Alquire (1990) described a geriatric clinic population in which 23 percent of the patients were active drivers at the time of the evaluation. Of the patients who drove, 60 percent had cognitive impairments and 40 percent were diagnosed with Dementia of the Alzheimer's type. Men continued to drive in the face of declining function significantly more often than did women (Carr et al., 1990).

In the Drachman and Swearer (1993) survey, 97 of the 130 AD patients who still drove, had done so for a period of 0.16 to 8.0 years (mean = 2.41 $\pm$ 1.78 years) post-AD. Thirty of the 97 AD patients were involved in 33 reported and unreported crashes while driving post-AD. Of the 58 patients who stopped driving post-AD, five did so because of crashes. At three years after the onset of dementia, 50 percent of the patients had stopped driving. In this same survey, it was discovered that after the onset of AD, 65 percent of the patients drove fewer miles, 34 percent drove the same amount of miles, and 1 percent drove more miles than they had before the onset of AD. Twenty-eight percent limited their driving to near home only, and 51 percent drove in familiar areas only. Twenty-one percent continued to drive anywhere. Forty-one percent of the AD patients who were still driving at the time of the survey were estimated to drive fewer than 5,000 miles per year, while 36 percent drove between 5,000 and 10,000 miles per year, and 23 percent drove more than 10,000 miles per year.

In a retrospective study, the driving records of 165 older drivers in British Columbia classified as having dementia were examined to determine whether cognitively impaired individuals experience a higher crash rate than their age- and sex-equivalent counterparts in the general population (Cooper, Tallman, Tuokko, and Beattie, 1993). The diagnosis of dementia was based on the consensus of a multidisciplinary team using criteria defined by the DSM III-R and the NINCDS-ADRDA (presented earlier). The average age at assessment was 69.2 years. The average severity of dementia was mild (mean = 3.18 on the Functional Rating Scale). Driver record data were extracted by the Traffic Safety Research Department of the Insurance Corporation of British Columbia (ICBC) using the provincial Motor Vehicle Branch (MVB) Drivers File and the MVB Accident Database and the ICBC Claims Database. These records were compared with those of a stratified random sample selected from the population of drivers in British Columbia, based on gender, exact year of age, and the area of the province in which the clinic patient lived. Since the period of time of interest was that between the time of symptom onset and cessation of driving for the demented sample, each matched pair of clinic and control drivers had the same period assigned, which was somewhat different from that attached to any other pair; this period of time varied from 6 to 70 months.

Crash records showed that the dementia group drivers were involved in 86 crashes during the driving period. This result is 2.5 times that found for the general driving population sample. Examination of the crash characteristics showed marked differences between the clinic and control group, as discussed below.

The demented drivers were *less* likely to have had their crashes at intersections than were the control group drivers (53 percent versus 87 percent, respectively). However, the clinic patients who had crashes at intersections were turning 42 percent of the time, whereas the control group drivers were turning in only 23 percent of their intersection crash involvements. The dementia group was twice as likely to have their crashes on wet roads (42 percent) as the control group (20 percent). The contributing factors to the crashes experienced by the dementia group drivers more often included improper turning or passing, following too closely, unsafe backing, or driving without due care or attention. This group was, however *underrepresented* with respect to right-of-way infractions such as failure to yield or disobeying a traffic control device (17 percent vs 53 percent for the control group drivers). The dementia group drivers were judged to be at fault in 92 percent of the crashes in which they were involved, compared to only 67 percent of their matched controls. Over 80 percent of the dementia group who experienced a crash event (and who were almost always at fault) continued driving for up to 3 years following the event, and during this time, over one-third had at least one more crash.

It is important to mention that a sample of 51 clinic subjects who did not meet the DSM III-R criteria for dementia was also evaluated in this study, and was involved in 2.2 times the number of crashes than their matched controls from the general driving population

(Tallman, Tuokko, and Beattie, 1993). This sample included individuals with neurological disorders not accompanied by dementia, psychiatric disorders, other medical conditions, and individuals with very mild memory problems. The not-demented group was significantly younger than the demented group, and the average duration of symptoms for the non-demented group was significantly shorter than for the dementia group. It was therefore deemed unwise in geriatric assessment settings to use the presence or absence of a diagnosis of dementia as a principal indicator of driving problems.

Previous work relating cognition to driving is largely based on younger subjects with heterogeneous types and severity of impairments. Studies of in-traffic driving tests have focused on populations with static or recovering cognitive deficits associated with stroke or head trauma (Galski, Ehle, and Bruno, 1990; Galski, Bruno, and Ehle, 1992; Nouri and Tinson, 1988; Sivak, Kewman, and Henson, 1981; and van Zomeren, Brouwer, Rothengatter, and Snoek, 1988). Driving evaluations have been typically unblinded and have relied upon non-standardized rating schemes that have lacked established validity or reliability. These studies are not generalizable to older drivers or to drivers with dementia specifically. Carr, Jackson, Madden, and Cohen (1992) demonstrated stability of driving skills in cognitively normal older drivers, using a standardized road test. However, there was no measure of reliability or validity for the road test and it was given in a "low intensity" setting on a college campus.

The recommendation that a diagnosis of dementia can be used to determine driver license revocation is premature and raises major concerns (cf. Drachman, 1988). The Friedland et al. (1988) and Lucas-Blaustein et al. (1988) papers recommended that patients with a diagnosis of Alzheimer's Disease should not drive. But their studies are limited by small sample sizes, retrospective design, and lack of data regarding amount and type of driving exposure. The Lucas-Blaustein study did not use controls. The Friedland study used community volunteer controls who appeared to be better than average drivers when comparing their reported crashes with population data (Kaszniak et al., 1991). Additionally, it has been reported that a substantial minority (almost one third) of drivers with Alzheimer's Disease may have preserved driving skills until advanced stages of their illness (O'Neill, 1992).

In this regard, Hunt (1991) examined the driving skills of persons in the questionable and mild stages of Senile Dementia of the Alzheimer's Type (SDAT) using an in-car, on-the-road assessment to study the differences in performance when compared with that of healthy older controls, and to assess whether those with SDAT lack insight into their driving skills. In this study, thirty-nine subjects with a mean age of 73 were assessed for the presence and level of SDAT using the clinical dementia rating scale (CDR), which rates cognitive performance in six categories (memory; orientation; judgment and problem solving; community affairs; home management including hobbies; and personal care). Thirteen subjects who received a score of 0 (no dementia) served as controls, and were compared to 14 mildly demented subjects (score = 1) and 12 questionably demented subjects (score = 0.5) who were matched for age, gender, education and driving experience.

The in-car driving skills were assessed during a one-hour trial by an investigator sitting in the back seat. An experienced driving instructor sat in the front passenger seat in a vehicle instrumented with a dual braking system to give directions and perform safety steering and braking if necessary. The self-assessment of driving skills included true/false questions about present driving skills and a self-rating of driving ability. The results of the on-the-road evaluation showed that all 13 of the control subjects passed the driving exam, as did all subjects with questionable dementia. However, 50 percent of the subjects with mild dementia failed the exam. The impaired subjects required repeated step-by-step directions while driving through the pre-designed route consisting of urban streets and highways, compared to what was required by control and questionably demented subjects to complete the course. The impaired drivers also needed verbal cues to signal when changing lanes throughout the driving task, whereas the unimpaired drivers may have initially forgotten, but would remember to signal on subsequent lane changes. Fifty percent of the impaired group, when they did signal, did so too late. Two of the impaired subjects stopped at green lights, and one stopped at a light to see what other drivers were doing. Almost half of the impaired group did not check their blind spots, compared to one-quarter of the questionably demented, and one-tenth of the control group. Additionally, impaired judgment by the demented group was noted by subjects coasting to near stop in moving traffic, drifting into other lanes, making sudden stops for no apparent reason, driving while pressing the brake and accelerator simultaneously, and failing to realize why other drivers honked at them.

Demented subjects' perception of their driving ability did not correspond either to that of their caregivers (as assessed by questionnaire) nor their actual driving performance. Eighty-six percent of the mildly demented subjects reported no problems with their driving ability. Seventy-one percent of the caregivers for this group reported concern about the subject's driving ability. They also reported that the subject is slower in reacting to dangerous driving situations (79 percent), and finds it difficult to join traffic (64 percent).

Based on these results, Hunt (1991) suggested that SDAT subjects are less likely to report driving problems than unimpaired drivers, and thus in-car assessment may be essential in determining driving fitness. Additionally, this report advocates measures of dementia *severity* rather than use of the SDAT diagnosis alone in determining licensing restrictions, because some persons with mild dementia still demonstrate driving fitness.

The focus of licensing decisions may better be reoriented toward functionally based measures rather than diagnostic labels, before devastating older patients with recommendations that profoundly alter their lives. The specific cognitive functions necessary for safe driving in maneuvering at intersections are in the preliminary phase of definition. With inadequate information about the relationship between clinical measures and driving, clinicians are often forced to rely on family observations to make determinations about driving safety.

Appropriate responses to traffic situations rely largely on intact attention and visuospatial skills. Demented drivers make a variety of typical errors while driving. The relationship between specific cognitive deficits and specific driving errors remains to be determined. Distractibility is likely to contribute substantially to errors in driving, especially at intersections and sites of merging traffic. Visuospatial skills are likely to relate to the ability of the driver to maintain appropriate vehicle placement or to judge distance and space relationships, such as required when monitoring oncoming cars or entering parking spaces

(Doege and Engelberg, 1986). Isolated memory loss may be relevant only when there is a change in routine, such as a detour or a sign to decrease speed for construction ahead. Isolated language impairment, especially a diminished reading comprehension, should have little impact in familiar settings. However, in unfamiliar settings there may be difficulty in interpreting important road signs. Simple reaction time is unlikely to play a major independent role in driving safety (Dubinsky, Gray, Husted, Busenbark, Vetere-Overfield, Wiltfong, Parrish, and Koller, 1991).

The trouble spots for normatively aged older drivers identified by analyzing crash data are not necessarily the same as for demented drivers. And no one knows how different older driver crash data would look if impaired drivers were not included in the statistics. It is likely, however, that older driver crash record statistics would improve substantially.

In conclusion, there is evidence that dementing disorders may contribute substantially to the increased crash risk of aging drivers. Although, we do not know what proportion of individuals with cognitive impairment/dementia continue to drive or what specific difficulties they encounter, studies suggest that it is common for demented individuals to drive and that they are at substantially increased risk for crashes. However, diagnosis is not an adequate predictor of function, since there is great heterogeneity in the rate of progress as well as the cognitive strengths and weaknesses among patients with dementing disorders. Diagnosis could thus be important as a way to identify persons for tracking, with decisions on whether driver status should be terminated then based on functional assessments. Certainly, performance-based guidelines for driving competence are essential, rather than dependence on diagnostic labels (Beattie, Tallman, Tuokko, and Weir, 1991). However, the specific cognitive functions necessary for safe driving remain to be determined.

With the proper identification of and intervention with impaired drivers, the crash statistics among cognitively intact older drivers may improve substantially. Many demented patients continue to drive who, as a group, appear to be at increased risk for crashes, when compared with controls. Some studies have shown significant relationships between cognitive and functional measures, driver status, performance on driving tests, and crash data. Unfortunately, a number of methodological problems in existing studies reduce the level of confidence to which the data can be generalized. Priority research issues in this area include:

- *How do we recruit representative samples? How do we avoid major selection bias?*

  Enrolling subjects with concerns about their driving skills is difficult because of the perceived threat to maintaining their driver's licenses. And yet, the drivers with self doubt are a crucial group to study.

- *Do the current studies have the power to make the conclusions they claim?*

  There are a number of issues that affect the generalizability of findings: (1) subjects are often Caucasian men with above average education; (2) the difficulty of a measure may be much greater than the driving circumstances in which many of the subjects ordinarily drive; (3) although significant correlations have been found between cognitive measures and driving performance, samples have been too small and/or the estimates too unstable to identify the independent contributions of each; (4) the relationships between memory/language and driving may partially reflect the procedures (for example, if a subject did not understand the directions, poor performance could be due to a comprehension problem rather than inherent difficulty with executing the task, and, even when the memory load is minimized by giving one direction at a time, some complex maneuvers require the ability to learn new information); and (5) a variety of cognitive deficits typically coexist.

- *Who should be the controls: the best drivers?, age matched?, young high risk?*

- *How do we know we've made a difference on clinical care, mobility, patient and public safety?*

  Crash data may be helpful for additional validation. However, crashes are relatively rare events. Exposure rates (that is, how much a person drives) and circumstances of driving are critical to understand the actual risk. Crucial exposure and situational data are often unavailable or unreliable, therefore limiting the use of crashes as an outcome measure.

OLDER DRIVERS' CRASH EXPERIENCE AND UNSAFE BEHAVIORS AT INTERSECTIONS

This section begins by providing evidence of a disproportionate level of involvement of older drivers in certain types of crashes at intersections. Specific pre-crash maneuvers and contributing driver behavioral factors, as well as problematic intersection features, geometric elements, and/or traffic control devices, are identified wherever such data are available in these crash analyses. A sampling of studies follows which attempt to go beyond the behavioral descriptions typical of police crash reports, drawing upon supplementary analyses of driver actions and inaction resulting in safe and unsafe performance at intersections, as well as the self-perceptions of difficulties in intersection negotiation by older drivers themselves.

AGE DIFFERENCES IN CRASH INVOLVEMENT AND INTERSECTION NEGOTIATION PROBLEMS

The crash experience of older drivers in this country and abroad has been widely documented. People age 65 and older represent about 12 percent of the population and about 14 percent of all motor vehicle fatalities. Compared to younger age groups, fewer older people have licenses, and they drive fewer miles per licensed driver. Yet, *per mile driven*, older drivers have higher crash rates than any other group except teenagers (Insurance Institute for Highway Safety [IIHS], 1986; Hildebrand and Wilson, 1990; Laux and Brelsford, 1990).

Based on National Highway Traffic Safety Administration (NHTSA) data describing crash rates and driver fatalities (Cerrelli, 1992), the risk of being involved in a crash drops sharply as a function of age, from 172 crash involvements per 1,000 licensed drivers in the teenage group, to a rate of less than 40 for drivers above the age of 60, *when statistics are based on the number of licensed drivers*. However, *when the crash involvement is adjusted for annual mileage*, teenagers still have the highest rate (which is seven times that for drivers ages 35 to 65), but the risk increases for drivers age 65 and older, with drivers age 85 and older having a rate almost three times as high as the average driver. The rate for female drivers age 85 and over is almost as high as the rate for teenage drivers.

Once involved in a crash, drivers in the oldest age group (age 85 and older) are more likely to be killed than all other drivers. When the driver fatality rate is calculated based on the estimated annual travel, the rate for drivers age 85 and older is 10 times that for drivers ages 30 to 60 (Cerrelli, 1992). As explored below, one of the principal reasons for the exaggerated crash rates of older drivers relates to problems of intersection negotiation.

A review of fatalities in 1985 and injuries in 1983 through 1985 showed intersection fatalities and injuries for older drivers (age 64 and older) to be 37 percent and 60 percent, respectively, of all older driver fatalities and injuries. In addition, older driver fatalities represented 20 percent of all driver fatalities at intersections (Hauer, 1988). Evidence of the problem is further brought into focus by distinguishing two older populations: the "young-old" or those under the age of 75, and the "old-old," a term usually applied to those age 75 and older. The National Safety Council's *Accident Facts* reports that crash involvement, both fatal and non-fatal, shows a rate per driver for drivers ages 65 to 74 that is the lowest for all age groups. By comparison, the fatal crash rate per driver is more than doubled and the non-fatal crash rate per driver is 29 percent greater for drivers age 75 and older (National Safety Council, 1990). Unfortunately, many sources of data on the (dysfunctional) behaviors of "older" drivers do not give separate statistics for newly-retired persons (i.e., up to age 70) versus the 75-and-older age group.

Older driver involvement in multiple-vehicle intersection crashes is further described in terms of a 1990 statistic compiled by the Insurance Institute for Highway Safety. As shown in Figure 2, percentages of fatal multiple-vehicle crashes that occur at intersections show a strong positive correlation with driver age. The level of involvement per 5-year age grouping climbs minimally up to age 55, moderately up to age 70, then more sharply for the groups ages 70-74 and 75 and older. At age 80 and older, half of the fatal crashes involving older people (age 65+) are of this type, compared to 26 percent or fewer for drivers up to age 50 (IIHS, 1991).

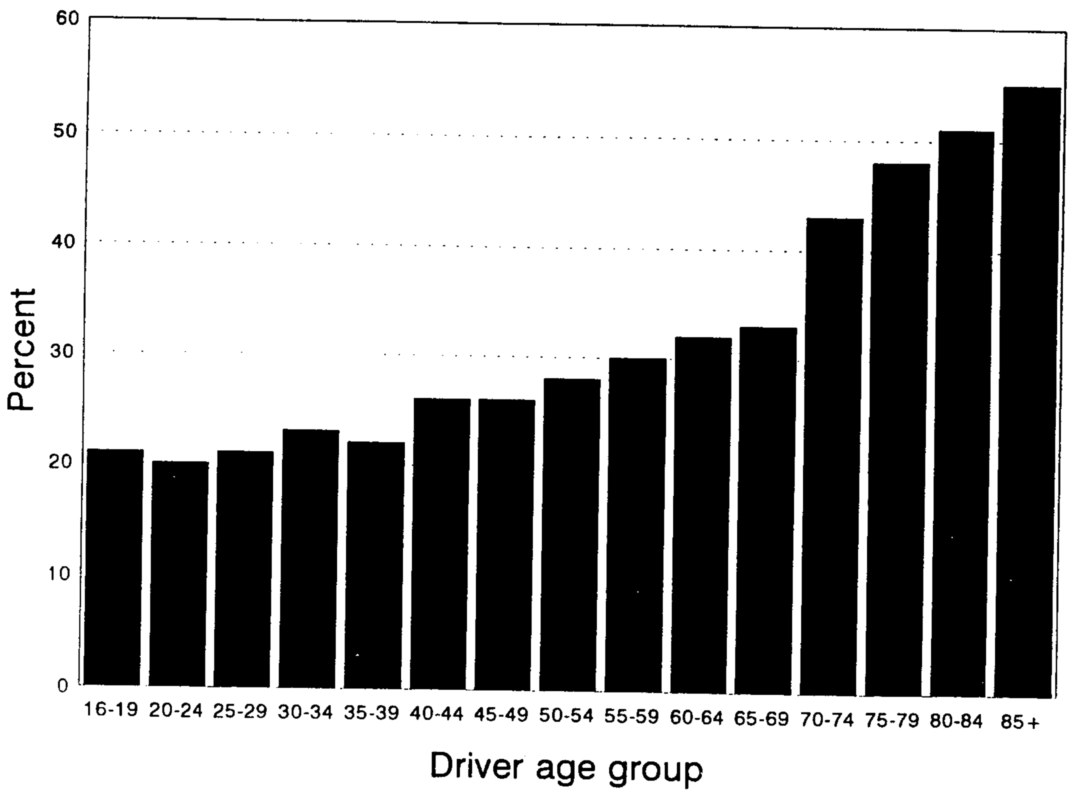

Figure 2. Percentage of drivers involved in multiple-vehicle intersection crashes by age. (IIHS, 1991)

Selected crash analyses are highlighted below that identify age differences in specific types of intersection crashes, and which advance hypotheses or lead into discussions relating to the role of intersection features (geometric elements), maneuver requirements, and/or traffic operations in accounting for older drivers' problems at these sites.

Staplin and Lyles (1991) examined crash reports from the state of Michigan for a three-year period (1986-1988) to determine relative involvement rates for drivers of different ages. In this analysis and discussion, the terms *relative involvement rates, involvement ratios,* and *over-* and *under-representation* and *over-* and *under-involvement* are keyed to implicit exposure levels for designated driver age groups, where the goal is to contrast differently aged drivers by comparing how often they are involved in crashes at intersections, versus the total number of times they negotiate these roadway features *without* incident.

Using induced exposure methods, field reports that coded *Driver 1* as the driver most at fault (or more causative of a crash) and *Driver 2* as the one less at fault (i.e., the "innocent victim" who was at the wrong place at the wrong time) formed the basis for calculating relative involvement rates. This allowed for the crosstabulation of event frequencies as Driver 1/Driver 2 ratios, by driver age group. The following four age groups, as dictated by the research sponsor for consistency with related investigations, were analyzed: age 26 and younger, ages 27 to 55; ages 56 to 75; and age 76 and older.

Crash report data were merged with other state-maintained files to create records for analysis that contained entries describing the crash 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, the vehicles involved, and the drivers' intentions. The crash records were screened to eliminate alcohol-involved crashes and analyzed in comparison with base conditions and defined by explicit variable limits. A subset of the analyses conducted is reported below as related to two intersection maneuvers on non-limited access roadways: (1) left turns into the crossing traffic stream; and (2) intersection crossing maneuvers.

The analysis set for *left turns into the crossing traffic stream* crashes contained roughly 15,500 incidents, in which just over 80 percent of the Driver 1's were turning left. The distribution of the four most common combinations of Driver-1 and Driver-2 intentions were:

- Driver 1 was turning left and Driver 2 was going straight (10,708).
- Driver 1 was going straight and Driver 2 was turning left (1,863).
- Driver 1 was passing and Driver 2 was turning left (about 600).
- Both drivers were turning left (about 400).

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 judgments, regardless of whether the signal is green or simply not present. Almost 75 percent of the crashes occurred during the day, 20 percent occurred at night, and the rest during dawn and dusk. About 70 percent occurred on dry pavement and more than 80 percent 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.

Crosstabulation data (Driver 1 Age by Driver 2 Age) for this maneuver are shown in Tables 4 and 5. These data are used to calculate involvement ratios by dividing the row percentage by the column percentage for a given age group. For left turns into crossing traffic, evaluation of the Driver-1 age distributions shows that the two older groups, ages 56-75 and ages 76-98, account for 16.2 and 6.4 percent of the crashes, respectively, when they are the left-turning driver (see Table 4). When going straight, their percentages decrease to 9.0 and 1.4 percent, respectively (see Table 5). Examination of the involvement ratios in Table 4 shows both groups of older drivers to be greatly overinvolved when they are turning left; only the 27-55 age group is underinvolved. However, when the "most at fault" driver is going straight (as shown in Table 5), only drivers age 26 and younger appear to be overinvolved.

Table 4. Crosstabulation of driver-1 age by driver-2 age, left turn maneuvers* (driver-1 turning left, driver-2 going straight).

Driver-1 Age	Driver-2 Age				
	≤26	27-55	56-75	76-98	Totals
≤26	1752	2251	393	39	4435 (41.4)
27-55	1521	1958	350	26	3855 (36.0)
56-75	663	855	205	14	1737 (16.2)
76-98	249	347	75	10	681 (6.4)
Totals	4185 (39.1)	5411 (50.5)	1023 (9.6)	89 (0.8)	10708

* Cell entries = number of crashes (row percentages)

Table 5. Crosstabulation of driver-1 age by driver-2 age, left turn maneuvers* (driver-1 going straight, driver-2 turning left).

Driver-1 Age	Driver-2 Age				
	≤26	27-55	56-75	76-98	Totals
≤26	359	464	86	18	927 (49.8)
27-55	271	372	89	9	741 (39.8)
56-75	54	84	25	5	168 (9.0)
76-98	9	11	6	1	27 (1.4)
Totals	693 (37.2)	931 (50.5)	206 (11.1)	33 (1.8)	1863

* Cell entries = number of crashes (row percentages)

These results indicate that older drivers do not appear to have a problem with drivers turning left across their paths, but do have a more serious problem when turning left in front of crossing traffic. Of course, there is a substantial difference in what is required of a given driver in one situation versus another. 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 or stop to allow the other motorist to make the crossing maneuver. However, when Driver 1 is making the left turn and Driver 2 is going straight, Driver 1 is likely to be stopped and must estimate time-to-collision, assess whether an appropriate gap in the traffic 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 (i.e., 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 older drivers' errors at intersections may be most frequently characterized by these problems. For other violations, older drivers had much lower relative-involvement ratios, though sample sizes were small.

Closer examination of these data revealed that the two older groups were overrepresented during the non-rush hour day period. The group age 76 and older had an involvement ratio greater than 6.0 while the age 26 and younger group had a ratio that was just over 1.0. There was, in essence, a trade-off between these two groups for the rush-hour and non-rush night periods. For the latter, the ratio of the age 26 and younger group had increased to about 1.2 while the ratio for the age 76 and older group had decreased to 3.8. The involvement ratios for the two middle groups were roughly the same, regardless of time of day; the group ages 27-55 was underinvolved and the group ages 56-75 was overinvolved. The older groups were always overinvolved in left-turn crashes, and the 76 and older group always had significantly more overinvolvement (especially during the day), with their worst problems occurring during non-rush hour day periods. Finally, bad weather and darkness decreased the degree of overinvolvement for drivers age 76 and older; involvement ratios were clearly higher for better environmental conditions.

Additional analyses of these data involved comparison with a baseline condition defined by *all* multi-vehicle crashes on U.S.- and state-numbered routes (including limited-access highways). Overall, left-turn crashes accounted for 6.5 percent of the base-condition crashes for drivers age 26 and younger, 6.0 percent for drivers ages 27 to 55, 8.9 percent for drivers ages 56 to 75, and 11.9 percent for drivers age 76 and older. Although this comparison is based on frequencies, it seems apparent that left-turn crashes are increasingly likely for older drivers. Summarizing for other variables, left-turn crashes relative to base-condition crashes were more likely for older drivers during daytime periods (30 percent versus 20 percent) and good weather (by about 5 percent), equally likely in urban areas (56 percent), and somewhat less likely to involve trucks as either Vehicle 1 or Vehicle 2.

It must be reiterated that the crashes used for left-turn crash analysis were specifically selected by crash type and driver intention. In general, there was no differentiation made between signalized and non-signalized intersections or by the number of lanes present. Nevertheless, older drivers evidenced serious problems making left-turn maneuvers into the crossing traffic stream. 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 crash records on the involvement of the older driver in left-turn type crashes. Though they may have chosen not to drive under adverse conditions, this would affect Driver 2 as well as Driver 1 counts, and the involvement *rate* should not be differentially affected.

For the analyses of *intersection crossing maneuver* crashes, different types of crossing maneuvers were separated. Specifically, non-signalized intersections were isolated, and mid-block, non-intersection crashes were not considered. The crosstabulation data are shown in Table 6. The difference in crash characteristics between this maneuver type and that considered above (i.e., left turn versus crossing) was of central interest in this analysis. This difference was examined by first investigating the differences between Driver 1 violations by age. For crossing crashes, 90 to 95 percent of all violations were for failure to yield the right-of-way, versus 70 to 75 percent for left-turn crashes. Most of the difference, however, was due to citations for improper signaling of a turn; this was cited for 20 to 25 percent of the left-turn crashes but less than 4 percent for crossing crashes. For crossing crashes, 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 for left turns. 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. On roads that were not dry, younger drivers shifted toward more speeding citations for crossing crashes, but again, there was little change for older drivers.

Table 6. Crosstabulation of driver-1 age by driver-2 age, crossing maneuvers* (angle-straight crashes at non-signalized locations).

Driver-1 Age	Driver-2 Age				
	≤26	27-55	56-75	76-98	Totals
≤26	986	1542	354	36	2918 (41.6)
27-55	794	1343	334	41	2512 (35.8)
56-75	355	586	132	26	1099 (15.7)
76-98	165	239	77	5	486 (6.9)
Totals	2300 (32.8)	3710 (52.9)	897 (12.8)	108 (1.5)	7015

* Cell entries = number of crashes (row percentages)

Comparing the results for left-turn crashes and crossing crashes provides a further indication that turning left across traffic is the more serious problem for older drivers. Of particular interest are the involvement ratios of the two older driver groups based on the data in Table 4 versus Table 6: for drivers ages 56-75 and 76-98, the Driver 1/Driver 2 ratios from Table 4 are 1.7 and 8.0, respectively, while these same ratios calculated from the Table 6 data are 1.2 and 4.5. This difference—which characterizes both older driver groups—may result from the contexts in which the drivers of turning versus crossing vehicles must perceive and react to conflicts: (a) 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 (b) for crossing maneuvers, the other vehicle is coming from the side. Although similar judgments must be made in these situations, the views to the approaching vehicles are 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 age 76 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 versus 13.1 to 13.8).

Overall, crossing crashes account for 3.1 percent of base condition crashes for drivers age 26 and younger, 2.9 percent for drivers ages 27-55, 4.6 percent for drivers ages 56-75, and 7.4 percent for drivers age 76 and older. Though the incidence of crossing crashes is exaggerated for older drivers, overinvolvement does not appear to be as great as it is for left-turn crashes.

Again using all multi-vehicle crashes on U.S.- and state-numbered routes as a baseline condition, a simple comparison of the percentage of crashes that each age group accounts for also shows that the representation of the two youngest groups is lower for crossing crashes than for the base condition (41.6 versus 44.2 percent for age 26 and younger and 35.8 versus 41.2 percent for ages 27-55) and higher for the two oldest groups (15.7 versus 11.4 percent for ages 56-75, and 6.9 versus 3.1 percent for age 76 and older). These percentages are very similar to those for left-turn crashes—about a point lower for the three youngest age groups and somewhat higher for the age 76 and older group. Similarly, for the age distributions comparing involvement as Driver 2 in left-turn and crossing crashes, respectively, to all multi-vehicle crashes, there are only modest differences (less than 2 percent). In general, the involvement ratios are lower for the two younger groups and higher for the two older groups when crossing crashes are compared with the base condition. Compared with left-turn crashes, the involvement ratios for crossing crashes are higher for drivers age 26 and younger and ages 56-75, and lower for the other two groups.

Comparisons between the intersection crossing crashes in this analysis set and the base condition for other factors showed the following:

- About 26 percent of the intersection crashes and approximately 30 percent of the base crashes occurred during non-rush night periods.
- Similar percentages of crashes occurred during clear or cloudy conditions (81.5 percent for crossing crashes and 78 percent for the base condition).

- Dry pavement accounted for 70 percent of the crossing crashes and 65 percent of base-condition crashes.
- A somewhat higher percentage of crossing crashes (52 percent) were rural crashes, versus 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 crashes compared to crossing crashes, 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, versus 13 to 14 percent for crossing crashes.

In summary, the analyses reported by Staplin and Lyles (1991) indicate that older drivers are relatively over-involved in both left-turn and crossing crashes at intersections. However, left turns into a crossing traffic stream appear to present more of a problem, in particular for drivers age 76 and older, than crossing the intersection.

The principal violation for all groups, but increasing with age in absolute terms, was failure to yield right-of-way. 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 versus left-turn crashes at unsignalized intersections showed that older drivers had more severe problems with turning left into the traffic stream 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 maneuvers more or less difficult were also examined. There appeared to be a traffic volume-related effect, although it was not consistent, and there appeared to be a greater problem for the oldest group when interacting with trucks.

Next, an analysis was conducted by Stamatiadis, Taylor, and McKelvey (1991) that looked specifically at age differences in crashes that occur at signalized versus non-signalized intersections. Data were obtained from records in the Highway Accident Master Files obtained from the Michigan Department of Transportation for the years 1983 through 1985, the Michigan Dimensional Accident Surveillance (MIDAS) Geometric Segment File, the MIDAS Traffic Volume File, and the Traffic Signal Inventory File. The Highway Accident Master File contains information about each highway crash that occurred, including location, roadway geometry and features, driving conditions, driver age and gender, driver responsibility for the crash, and vehicle information. The MIDAS Geometric Segment File contains such information as number of lanes, lane width, roadside development, speed limit, and roadway curvature for each unlimited access segment of the state trunkline system in Michigan. The MIDAS Traffic Volume File contains capacity, average daily traffic, and hourly traffic volume information. The Traffic Signal Inventory File contains information about the types of traffic control devices present, as well as signal phase information.

Data from 124,000 two-vehicle crashes (54,000 crashes at signalized intersections and 70,000 crashes at non-signalized intersections) showed that drivers below the age of 25 and over the age of 65 were overinvolved in crashes at both types of intersections. However, the overinvolvement of older drivers in non-signalized intersection crashes was more pronounced than it was for signalized intersection crashes. Figure 3 shows the relative crash involvement ratio by driver age for both signalized and non-signalized intersections.

Analyses were conducted to examine the relationship between driver age and crashes as a function of lighting condition (day versus night), pavement conditions (wet versus dry), and for the impact of signal phasing (signalized intersections) and signing (non-signalized intersections). Also, intersection collision types and crash severity were studied for the older driver crashes in the database. Age differences in crash involvement as a function of these variables are discussed below.

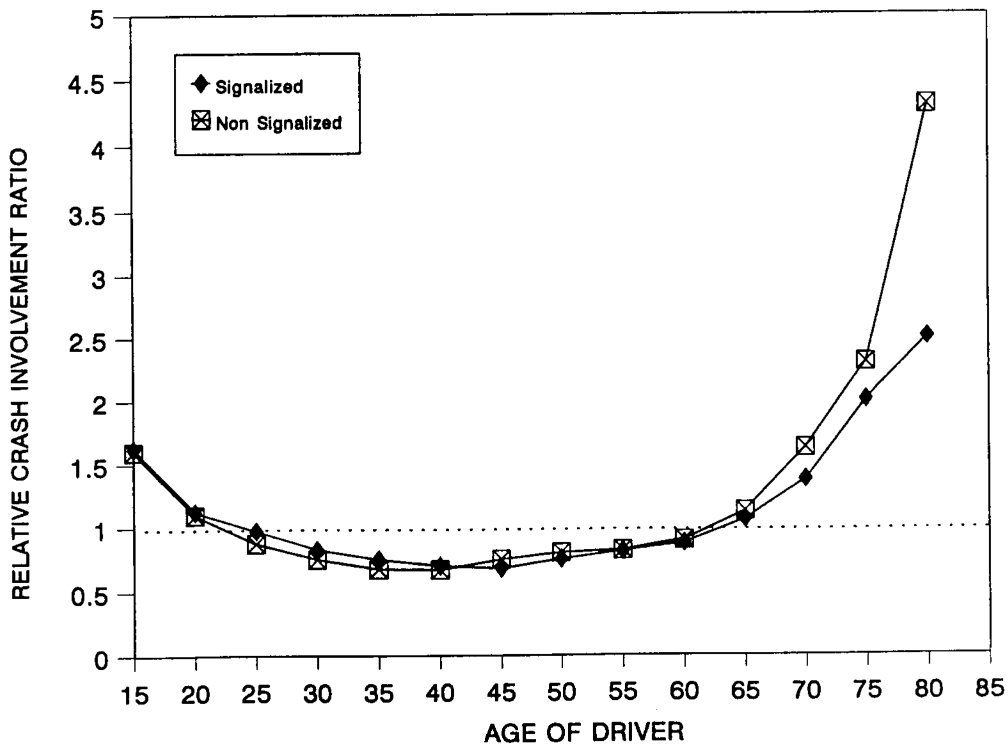

Figure 3. Comparison of the relative crash involvement ratio for signalized and non-signalized intersection crashes. (Stamatiadis et al., 1991)

- *Lighting condition:* Examination of the relative crash involvement of drivers both during the day and at night at both signalized and non-signalized intersections indicated that there was no significant difference between crash involvement during day and night conditions for any particular age group.

- *Pavement condition:* At non-signalized intersections, older drivers showed slightly higher crash involvement on dry pavement than on wet pavement, which is opposite that of the young drivers. At night, there was no difference in older drivers' crash involvement under wet or dry pavement conditions, whereas drivers in the other age groups had slightly higher crash involvement at night under wet pavement conditions. At signalized intersections the crash involvement ratios for all drivers was similar to that found for non-signalized intersections, however the performance of older drivers showed more variability under wet pavement conditions.

- *Traffic signs (stop and yield):* Although the total number of crashes was reduced at non-signalized intersections that contained signs when compared to unsigned intersections, the crash involvement ratios of older drivers was higher at signed intersections than at unsigned intersections. It is hypothesized that older drivers' problems at signed intersections relate to visual acuity, reaction time, or interpretation. Perhaps, however, the higher traffic volume associated with signed intersections taxes the abilities of older drivers to perform driving functions that would not be affected under lower-volume conditions, which would exist at unsigned intersections.

- *Signal phasing:* The relative crash involvement ratios for older drivers were higher at two-phase (no turning phase) signalized intersections than for multi-phase (includes turn arrow) signalized intersections, highlighting problems older drivers may have determining acceptable gaps and maneuvering through traffic streams when there is no protective phase. Further, crash percentage increased significantly for older drivers when an intersection contained flashing controls, as opposed to conventional (red, yellow, green) operations.

- *Crash type:* Four crash types were examined at both signalized and non-signalized intersections to determine the relative frequency with which older drivers were involved in a particular crash configuration. Rear-end crashes were defined as collisions which occurred when two vehicles were traveling in the same direction. Right-angle crashes were defined as collisions in which one vehicle was traveling straight on a major road and the other was traveling straight on a minor road. Head-on and left-turn crashes were collisions at an intersection in which vehicles were moving in opposite directions and collided head-on, or one of the vehicles turned left, resulting in a collision with the vehicle traveling straight ahead. Other angle crashes were defined as collisions where one vehicle was moving straight and the other turned right.

  Results showed that older drivers were most frequently involved in rear-end and right-angle crashes at both signalized and non-signalized intersections, and the greatest percentage of fatalities to older drivers occurred as a result of right-angle collisions. At signalized intersections, right-angle collisions and head-on/left-turn collisions accounted for approximately 47 percent and 20 percent of the older driver fatalities, respectively. Older driver injuries most frequently resulted from rear-end collisions (38 percent), followed by right-angle collisions (25 percent) and head-on/left-turn crashes (15 percent) at signalized intersections. At non-signalized intersections, the highest percentage of fatalities were the result of right-angle collisions (25 percent), with the other three crash types following at similar frequencies (between 5 and 10 percent). In terms of the frequency of injury at non-signalized intersections, rear-end crashes were the most frequent cause (35 percent), followed by right-angle crashes (18 percent), other-angle crashes (10 percent), and head-on/left-turn crashes (8 percent). The higher speeds and heavier volumes at signalized intersections may account for the greater percentages of fatalities resulting from right-angle and left-turn collisions, where drivers are possibly running the yellow light (right-angle collisions), and making unsafe gap acceptance decisions during unprotected left turn signal phases.

- *Violations:* Failure to yield right-of-way was the leading violation type for all older drivers, followed by following too closely, improper lane usage, and improper turning.

- *Number of lanes:* At non-signalized intersections, older drivers showed the highest crash frequency on major streets with two lanes in both directions (a condition most frequently associated with high-speed, low-volume rural roads), followed by roads with four lanes, and those with five lanes in both directions. For signalized intersections, the greatest crash frequency occurred on major streets with five lanes, followed closely by roadways with four lanes. These sites were most often associated with low-speed, high-volume urban locations, where intersection negotiation involves complex decisions involving more conflict vehicles and more visually distracting conditions.

In a study of 7,000 intersection crashes between 1986 and 1988 in Virginia involving drivers age 50 and older, Garber and Srinivasan (1991) examined variables including driver age, crash location, driver gender, type of collision (rear end, angle, head on, sideswipe same direction, or sideswipe opposite direction), vehicle maneuver, driver action, and type of intersection and traffic control. Two types of statistics were calculated to describe crash involvement. First, a simple *percentage of involvements* (by driver age) measure for each variable named above was calculated, by dividing the number of drivers in a specific age group who were involved in a particular crash type (or crash location, vehicle maneuver, etc.) by the total number of drivers involved in that same crash type (location, etc.).

In addition, an *involvement ratio* was calculated by dividing the number of "at fault" crash involvements for a given level of each variable by the number of involvements not associated with crash causation. Specifically, the involvement ratio for a particular crash type (or crash location, etc.) was calculated by dividing the number of drivers in a given age cohort deemed "at fault (based on violation codes) by the number in the same age group who were involved in the same crash type (crash location, etc.) but were *not* at fault.

First, with respect to data describing *crash location*, proportionality tests showed that the percentage of involvements at intersections for drivers age 65 and older was significantly higher ($p \leq 0.001$) than that of the drivers ages 50-64. For drivers above age 62, the involvement ratio at intersections was higher than the involvement ratio at all locations combined. Looking further at the type of traffic control at intersections where crashes occurred (stop sign, traffic signal, or none), proportionality tests showed that the percentage of involvements at stop-controlled intersections for drivers age 65 and older was significantly higher than that for drivers ages 50 to 64. Both driver age groups had a higher percentage of their crashes at signalized intersections than at stop-controlled intersections, but there was no significant difference in the proportionality rate for signalized intersections by driver age group. The involvement ratio at intersections with no control was significantly higher than the involvement ratio at intersections with traffic signals, for drivers ages 50 to 64. For drivers age 65 and older, the involvement ratio for crashes at intersections with stop control was higher than the involvement ratio for intersections with no control.

Next, with respect to the *type of vehicle maneuver* when the crash occurred, it should first be noted that the predominant crash maneuver for *all* age groups was going straight.

This is a simple fact of exposure: straight-ahead travel accounts for a far greater proportion of driving than turning maneuvers. However, for groups older than age 54, the percentage-of-involvements measure calculated by Garber and Srinivasan indicated that there was a consistent reduction in the percentage of crashes for a vehicle going straight and a concurrent *increase* in the percentage of crashes for vehicles turning left. Also, the results of the proportionality test showed that individuals 65 and over had a significantly higher level of left-turn crashes than drivers ages 50 to 64. An increase in the proportion of involvements involving right-turning vehicles was also observed for the older drivers as a function of increasing age; however the proportion of right-turn crashes was not statistically different than that for the drivers ages 50 to 64. Similarly, the involvement ratios calculated for crashes involving left turns were higher than those for going straight and turning right for all age groups; but, significant increases were observed for drivers age 64 and older. Results of *t*-tests for drivers ages 50 to 64 and those age 65 and older showed significantly higher involvement ratios for right- and left-turn maneuvers than for going-straight maneuvers.

With respect to *type of collision*, proportionality tests showed that although angle collisions were most common for all age groups, this type of collision increased with age, and accounted for 61 percent of the collision types for drivers over age 65. For drivers age 65 and older, there was an increase in the involvement ratio of angle, sideswipe (same direction), and head-on collisions with increases in age, and the involvement ratio for each of these collision types was significantly greater than for rear-end collisions; thus, it was concluded that failure to yield the right-of-way was a particular problem for older individuals.

A number of driver actions were considered in this analytical study, including "exceeding the speed limit/exceeding safe speed;" "failure to yield the right-of-way;" "following too closely;" "inattention;" "disregarded traffic signal indication;" "disregarded stop/yield sign;" and "other." The most common violation for all drivers over age 50 was "failure to yield the right-of-way;" however, drivers age 65 and older showed a significantly higher proportion of failure-to-yield violations than those ages 50 to 64. A significantly higher proportion of older drivers were charged with "driver inattention," "disregarding a signal control," and "disregarding a stop/yield sign" than drivers ages 50 to 64. Drivers ages 50 to 64 were more often charged with speeding than their older counterparts.

Calculations based on gender showed that female drivers had significantly higher involvement ratios than male drivers, for the age group 50 to 64 and also for drivers age 65 and older.

Garber and Srinivasan developed a statistical model to relate the risk of crash involvement to the traffic and geometric characteristics of an intersection. Results of the modeling indicated that older drivers—defined as drivers ages 65 and above—are more at risk of committing a traffic violation when they are required to yield to opposing traffic, compared to other age groups.

In another effort to describe age differences in crash involvement, Cooper (1990) utilized a database of all 1986 police-attended crashes in British Columbia to compare the crash characteristics of older drivers with those of their younger counterparts. The database consisted of 2,962 drivers ages 55-64, 2,018 drivers ages 65-74, 873 drivers ages 75 and older, and 8,210 middle-aged drivers between the ages of 36-50. Variables relating specifically to older drivers' overinvolvement in intersection crashes are described below.

While 66.5 percent of 36-50 year old drivers' crashes occurred at intersections, the percentage increased to 69.2 percent, 70.7 percent, and 76.0 percent for drivers ages 55-64, 65-74, and 75 and older, respectively. An analysis of the pre-collision driver actions (the driver action immediately preceding the crash sequence) showed that older drivers were turning more often than middle-aged drivers. While only 19.3 percent of pre-collision actions for the drivers ages 36-50 involved turning, the proportion rose significantly to 22.2 percent for drivers ages 55-64, 26.6 percent for drivers ages 65-74, and 32.9 percent for drivers ages 75 and older. These proportions were almost identical when pre-collision actions were examined for crashes occurring at stop sign versus signal controlled intersections.

Intersection crossing collisions accounted for a greater proportion of older drivers' crashes than for those of the middle-aged driver group; the proportions increased from 30.1 for the drivers ages 36-50 to 32.7, 36.9, and 38.7 percent for drivers ages 55-64, 65-74, and 75 and older, respectively. Similarly, crashes involving vehicles in the act of turning were more frequent for older drivers, especially for those in the oldest group. The proportion of rear-end collisions *decreased* as a function of increasing age, however.

Overall, the two oldest groups identified in this analysis were significantly more crash involved at stop/yield sign locations and less involved at either uncontrolled or signal-regulated locations. In follow-on questionnaires administered to a sample of drivers in each age group studied, intersection negotiation was mentioned by the older drivers as second in difficulty to problems changing lanes. About 20 percent of the older drivers mentioned not stopping properly at red lights, and especially stop signs, and 41 percent said they ran amber lights. Fifty percent of the drivers over age 75 reported running amber lights. Responding specifically about difficulties with signs, older drivers ages 65-74 stated that sign placement caused difficulty (44 percent), and an almost equal percentage mentioned that the size of the sign and/or size and clarity of the lettering posed problems (46 percent). For drivers age 75 and older, sign size/letter size and clarity posed greater difficulty (54 percent) than sign placement (38 percent).

Vehicle maneuvering prior to the crash was a key variable for drivers over age 65, and in particular, for left turns at uncontrolled or stop/yield sign-controlled intersections. Drivers ages 36-50 experienced only 10.9 percent of their crashes while turning left at this type of intersection, compared to 13.0, 15.4, and 19.5 percent of drivers ages 55-64, 65-74, and 75 and older, respectively. In the questionnaire survey, approximately one-fourth of the older drivers reported that turning left at uncontrolled intersections either sometimes or frequently was troublesome; the percentage stating it was troublesome rose with age from 21 percent of drivers ages 55-64 to 28 percent of drivers age 75 and older.

As age increased, intersection-related driver errors such as failure to yield the right-of-way and ignoring a traffic control device also increased. These percentages were 12.5 percent and 3.1 percent, respectively, of police-assigned contributing factors among crash-involved drivers ages 36-50; 17.3 and 3.8 percent, respectively, among drivers ages 55-64; 24 and 4.9 percent, respectively, among drivers ages 65-74; and 32.6 and 6.4 percent, respectively, of drivers ages 75 and older. Interestingly, very few of the questionnaire respondents cited failure-to-yield as a prime driving fault; however, disobeying a traffic control device was cited as a more frequent mistake. Failure-to-yield was expressed by less than 2 percent of the older drivers interviewed as their most frequent fault, and 20 percent mentioned ignoring a traffic control device. The overall crash data, however, produced values of 22 percent and 5 percent, respectively, for failure-to-yield and disobeying a traffic control device. These findings suggest that older drivers may not be aware of actions that contribute to crash risk at intersections.

Finally, Council and Zegeer (1992) conducted an analysis of intersection crashes occurring in Minnesota and Illinois for the time period between 1985-1987 to highlight crash types, situations, and causes of crashes to increase the knowledge of how older drivers react at intersections. For all the analyses, comparisons were made between a "young-old" group ages 65-74, an "old-old" group, age 75 years and older, and a "middle-aged" comparison group of 30-50 year olds. In some cases, the contributing factors and pre-crash maneuvers of a crash involving one older driver and one middle-aged driver could be analyzed, to help account for sources of differences in the data due to characteristics of intersections where each driver age group may most frequently drive.

The crash types occurring at both urban and rural signalized and stop sign controlled intersections, along with the type of vehicle maneuver executed prior to the crash were examined using data from both States. Contributing factors were then analyzed in turning and angle crashes using the Minnesota data to determine whether the crashes were a result of the driver's disregard for a traffic signal, lack of attention, failure-to-yield, or some other factor. This analysis was restricted to crashes in which both a middle-aged and an older driver were involved. Finally, the older driver and middle-aged driver crashes in Minnesota were linked with the Minnesota Intersection File, which contains approximately 600 signalized intersections, in the development of a linear regression model which predicted older driver crashes as a function of entering vehicles and intersection characteristics. Details of the analyses are described below for the crash types, the pre-crash maneuvers at both signalized and stop controlled intersections, the contributing factors in angle and turning collisions, and the modeling of Minnesota intersection data.

- *Collision type at signalized intersections*: Examination of the Minnesota crash data file showed that drivers ages 75 and older were more likely to be involved in left-turn crashes at urban signalized intersections than drivers ages 30-50 and drivers ages 65-74 (30.2 percent compared to 25.2 percent and 26.8 percent, respectively). Also, both the young-old and the old-old groups were more likely to be involved in left-turn crashes at rural signalized intersections than middle-aged drivers (33.5 and 31.7 percent, respectively, compared to 27.5 percent). Right-angle collisions were also more prevalent among both groups of older drivers at both rural and urban intersections than for the middle-aged group. Middle-aged drivers at both urban and rural signalized intersections had a greater percentage of rear-end collisions than their older counterparts.

Examination of data from the Illinois crash file for the same time frame showed the same patterns for signalized intersections. While the Illinois data combined both left- and right-turning crashes into one category, it appeared that the older drivers were overrepresented in turning crashes at both urban and rural locations. At urban locations, turning crashes accounted for 37.1 percent of the middle-aged driver crashes, compared to 42.9 percent of the young-old and 50.1 percent of the old-old driver crashes. At rural locations, the percentages increased slightly to 37.5, 43.6, and 53.3 percent for the middle-aged, young-old, and old-old groups, respectively.

- *Collision type at stop-controlled intersections*: Analysis of the Minnesota data showed little difference in the proportion of crashes involving left-turning vehicles at either urban or rural locations when the older groups are compared to the middle-aged group. There was, however, a significant over-involvement for both groups of older drivers in right-angle collisions, both in urban and in rural locations. At urban intersections, right angle collisions accounted for 56.1 percent of the middle-aged driver crashes, compared to 64.7 percent of the young-old and 68.3 percent of the old-old driver crashes. These percentages increase for all groups at rural intersections, 61.3, 68.6, and 71.2 percent, respectively for middle-aged drivers, young-old drivers, and old-old drivers. Data for yield-sign controlled intersections showed older drivers over-contributing to left-turn collisions in urban areas, and in angle collisions in both urban and rural areas.

- *Pre-crash maneuvers at signalized intersections*: Regardless of the crash type involved (right-angle, left-turning, right-turning, sideswipe, or rear-end), the middle-aged driver was more likely to be going straight and the older driver was more likely to be performing a turning maneuver at both rural and signalized intersections. This difference was least noticeable for right-angle crashes, where the percentages of drivers going straight were 79.7 and 80.1 percent for the two age groups; however, the trend was that the middle-aged drivers were more likely to be slowing or stopping, and the older drivers were more likely to be turning left or right-on-red. With respect to left-turning collisions at urban locations, 49.1 percent of the middle-aged drivers were going straight and 44.1 percent were turning left. This compares to 25.9 percent and 66.2 percent, respectively for the young-old drivers, and 14.9 and 80.8 percent, respectively for the old-old drivers.

  For right-turning collisions at urban locations, 44.5 percent of the middle-aged drivers were going straight compared to 32.1 percent of the young-old drivers and 21.4 percent of the old-old drivers. Turning right however, accounted for 35.8, 39.3, and 42.9 percent, respectively of the middle-aged, young-old, and old-old drivers' crashes at urban locations. It appears that for right-turning crashes, the middle-aged driver is most likely crossing the intersection on a green signal and the older drivers are turning right on a red signal in front of the oncoming middle-aged driver. Similar patterns emerged for the rural signalized intersection pre-crash maneuvers, with middle-aged drivers most often traveling straight, and older drivers most often turning left or right.

- *Pre-crash maneuvers at stop-controlled intersections*: For both rural and urban locations, right-angle collisions were the most frequent collisions, and middle-aged drivers again were more likely to be traveling straight, or slowing/stopping than the two older groups. The older drivers were more likely to be turning left or starting from a stop than their younger counterparts. This pattern is similar for left-turning crashes. For rear-end collisions, the old-old drivers were more likely to be going straight (thus being the striking vehicle), and the middle-aged and young-old were more likely to be stopped or slowing. For the few right-turning collisions at urban stop-controlled intersections, the middle-aged drivers were going straight and the old-old drivers were more likely to be turning left or right, or starting from a stop. Rural stop-controlled locations showed the same patterns of pre-crash maneuvers among the three age groups.

- *Contributing factors in angle and turning collisions*: For both rural and urban signalized locations, the middle-aged group was much more likely to be identified by the police officer as having exhibited "no improper driving." This occurred in 65 percent of the incidents for this age group, compared to 30.7 percent of the young-old, and 13.4 percent of the old-old. By comparison, the older driver groups were more likely to be cited for failing to yield (31.9 percent of the young-old, 42.0 percent of the old-old, and 10.9 percent of the middle-aged drivers); disregarding the stop sign (22.0 percent of the young-old, 30.7 percent of the old-old, and 10.3 percent of the middle-aged drivers); and driver inattention (8.9 percent of the young-old, 8.2 percent of the old-old, and 6.4 percent of the middle-aged drivers).

Analyses of citations given for particular pre-crash maneuvers were conducted. For left-turning situations at signalized intersections, the middle-aged driver was more likely to be characterized by "no improper driving," while the older drivers were more likely to fail-to-yield and to disregard the traffic signal. For going straight, the middle-aged driver was again more likely to exhibit no improper driving behavior, while the older drivers were cited with disregarding the signal.

Breakdowns of contributing factors for the urban and rural stop-controlled intersections also showed that the middle-aged drivers exhibited a higher proportion of no improper driving behavior, while the young-old and old-old groups were more often cited for failure-to-yield, disregarding the stop sign, and driver inattention. When starting from a stop, however, the old-old drivers had a *lower* probability of being cited for improper driving. When cited, the old-old drivers were more likely to have disregarded the stop sign than the other two driver groups. The young-old as well as the old-old drivers more frequently failed to yield than the middle-aged drivers. The middle-aged drivers were more likely to be cited for driver inattention.

For left turns at stop-controlled intersections, the middle-aged drivers again were more frequently found to have exhibited "no improper driving." The two older driver groups were most frequently cited with failure-to-yield. There was no difference in the number of drivers in each age group who disregarded the stop sign. For going straight situations, the middle-aged driver was found to have exhibited no improper driving behavior twice as often as the young-old drivers, and almost three times as often as the old-old drivers. Failing-to-yield, disregarding the stop sign, and inattention were most often cited as the contributing factor for the two older groups.

- *Modeling of Minnesota intersection data*: A sample of 600 signalized intersections were selected from the location-based records in the Minnesota Intersection file, and were linked to the intersection crashes just described. Records were then built which contained specific intersection characteristics and counts of crashes for the middle-aged group and for the combined older driver group, in an attempt to extract variables which would explain the difference in the proportion of crashes occurring for each age group. Only two of the variables examined (number of entering vehicles, and maximum speed limit on one of the incoming legs) explained any of the variance between the two groups' crash numbers, and the amount of variance explained was only 20 percent. None of the other variables examined (type of intersection, fixed versus variable signal phase, or the general and specific environmental character of the surrounding area) were significant predictors. Notably, while the number of older driver crashes increased with entering vehicles, it did not increase as rapidly as the number of crashes involving middle-aged drivers. This result was attributed to the possibility that older drivers were removing themselves from high volume locations, more often than middle-aged drivers.

In summary, the Council and Zegeer (1992) analysis found that both young-old and old-old drivers have difficulty negotiating intersections, and these difficulties often involve left-turn maneuvers at signalized intersections, and turning or entering maneuvers at stop-controlled intersections. Finer analysis of the crash types (left turns, and angle collisions) and violation types (failure-to-yield and disobeying traffic control devices) highlight the older driver's difficulty in judging safe gaps; detecting targets in their periphery; and detecting, comprehending and responding to signs and signals within a timeframe for the safe completion of intersection maneuvers. Urban signalized intersections were associated with a higher percentage of older driver involvements in rear-end and turning crashes when compared to stop-controlled intersections. At stop-controlled urban intersections, however, the percentage of drivers ages 75 and older involved in right-angle crashes was more than double that of urban signalized intersections.

OLDER DRIVERS' UNSAFE BEHAVIORS LEADING TO INTERSECTION NEGOTIATION PROBLEMS

Many analyses have included efforts to determine the types of maneuvers that create problems for older drivers, the classes of roadways on which older drivers are having problems, traffic control devices that cause difficulties for older drivers, and other reasons for older driver intersection crash involvement. These issues have been addressed, to an extent, in the previous reports of age differences in crash involvement rates: for example, the often-cited reason for older driver intersection crash involvement as failure-to-yield (Brainin, 1980; McKnight, Simone, and Weidman, 1982; McPherson, 1985; Cooper, 1990; Hildebrand and Wilson, 1990; Staplin and Lyles, 1991; IIHS, 1991). The material in this section, while reinforcing this finding, is also intended to supplement the previous discussion with more detailed information describing specific unsafe *behaviors* preceding older driver intersection crashes. These findings were derived from a variety of analytical approaches and older driver self-report data.

In an analysis of 124,329 two-vehicle crashes from the NHTSA's 1984-1986 Crash Avoidance Research Datafile (CARDfile), Campbell (1993) characterized the physical sequence of events prior to a collision at an intersection, as a part of a larger research effort to address vehicle-based collision-avoidance technology. Two intersection collision types were considered: intersection crossings, where both vehicles travel straight ahead, and turning maneuvers, where one driver makes a left turn across the path of an opposing through driver. Intersection crossing crashes were about twice as frequent in the police reports as opposite-direction turning crashes, and accounted for 13 percent of all police-reported crashes.

Signs and signals were associated factors in crossing path crashes at intersections, and were associated with 81 percent of the crashes (as opposed to alcohol, darkness, snow, or ice), in the CARDfile analysis. There were interesting differences between the crashes that occurred at signed and signalized intersections. Nearly all the crashes at the signalized intersections were the result of a driver entering the intersection against the red light. Although there was no strong pattern in the ages of the drivers behaving in this manner, there was some overrepresentation of older drivers. There were two patterns of behavior associated with stop-controlled intersections: failing to stop at the sign, and first stopping at the sign and then proceeding into the right-of-way of the other driver. Sixty-nine percent of the drivers that first stopped and then pulled out in front of the other vehicle were over age 60.

For the intersection collisions involving turning maneuvers, age distributions were examined for the turning driver as compared to the driver going straight. About 19 percent of the turning drivers were over age 56, while only 9 percent of the drivers going straight through were over age 56. While these data do not take exposure into account, they suggest a substantial "overinvolvement" by older drivers as the turning driver, yet this group still accounts for only 20 percent of the offending drivers.

In an earlier analysis of NHTSA's Multiple Disciplinary Accident Investigation of 2,076 drivers cited as responsible for a crash, Brainan (1980) reported that failure to yield the right-of-way increased most markedly with driver age, from about 21 percent in the younger group (ages 25-44) to 48 percent in the group age 75 and older. In addition, disobeying signs and signals (primarily missing stop signs and traffic signals) showed a sudden increasing trend with increasing age, starting at about age 70, with 40 percent of the drivers over age 75 making errors associated with these traffic control devices (TCDs). Changing direction unsafely also represents a major error committed by older drivers. In this area, common charges are improper turns, inaccurate turning (especially for left turns), and careless or improper lane changing. In addition older drivers frequently create crashes by suddenly stopping in the stream of traffic to reorient themselves upon realizing that they have missed a turn; in these crashes, they are the victims of a rear end collision (McKnight, Simone, and Weidman, 1982). Maintaining speed and proper path through turns have also been reported as problems for older drivers (McKnight and Stewart, 1990).

Brainan (1980) used in-car observation to gain firsthand knowledge and insight into older person's driving behavior. Seventeen subjects ages 25-44, 81 subjects ages 60-69, and 18 subjects age 70 and older drove a test vehicle through a standardized test route while an observer in the passenger seat rated driving performance. The test route was approximately

9 km (5.6 mi) and took 15 to 20 minutes to traverse. Legal speed limits varied from 40-88 km/h (25-55 mi/h), and the course contained the following intersection driving behaviors: stopping at stop signs (6 times); turning left (4 times); turning right (4 times); responding to traffic lights (9 times); driving in traffic and vehicle control on standard streets in traffic situations (rated 3 times); speed maintenance on standard streets (rated 3 times); changing lanes (1 time); and selection of a lane in response to sign and pavement marking (1 time). Other behaviors relating to driving in highway environments, negotiating curves, and backing were also observed and evaluated. The overall results of the experiment showed a significant total score difference between the three age groups, with the drivers ages 25-44 having the highest (safest) score, followed by the drivers ages 60-69, and those age 70 and older. The two older age groups in particular showed more difficulty making right and left turns at intersections, and in handling traffic lights at intersections. The left-turn problems resulted from a lack of sufficient caution and poor road positioning during the turn. Right-turn difficulties experienced by the oldest group were primarily as a result of failing to signal. The drivers age 70 and older had difficulty at two of the stop signs; their errors were in failing to make complete stops, poor vehicle positioning at stop signs, and jerky and abrupt stops. The single difficulty exhibited by the drivers ages 60-69 that was not shared with the oldest group was lack of enough caution at a traffic light. Here, they were either jerky and abrupt, did not stop when they should have, or they did not show sufficient caution.

Next, a re-analysis of the Michigan intersection crash data presented in the beginning of this section (Staplin and Lyles, 1991) deserves mention. A detailed, crash-by-crash review of approximately 700 crashes was conducted, resulting in an anecdotal determination of the reasons for each incident and a description of older driver behaviors as contributing factors (Staplin, Harkey, Lococo, and Tarawneh, 1997).

In the state of Michigan, a crash report is supposed to be filed for every crash occurring on public roads. There is, however, considerable information on the crash report which is not coded as part of the crash database. This information includes sketches of the crash scene and written comments made by the investigating police officer. Information that can be gleaned from these sources on the crash report includes, for example, where in the intersection the crash actually occurred, comments made by the drivers and witnesses regarding "what happened," and the positions of other, non-involved but possibly contributing, vehicles in the vicinity of the crash. It is this type of data that provided the basis for the anecdotal analysis.

The crash data that were reviewed for this analysis primarily came from Troy, Michigan (a fast-growing suburb of Detroit). Troy includes a variety of highway situations ranging from residential streets to boulevard-type arterials with high volumes. The procedure was to identify a set of crashes involving older drivers (either as the at-fault or "other" driver) in the statewide crash database and then retrieve the hard copy of the written crash report form for analysis.

In general, the types of crashes in which older drivers were involved were consistent with what would be expected from the review of the literature: for example, older drivers had problems in yielding the right-of-way and in making left turns. The order in which the crash types are discussed below does not necessarily reflect increasing or decreasing crash severity or frequency.

- *Good Samaritan crashes:* A typical "good samaritan" scenario is one where a driver wishes to turn left out of a parking lot across three lanes of traffic approaching from the left and merge with traffic approaching from the right. The first two lanes of traffic stop and "wave the driver through" only to have the turning driver hit by a driver in the third lane, which may be less congested with faster-moving vehicles. Older persons were often noted as the driver who wanted to make the left turn. There were also several instances where it was an older driver in the third lane that hit the turning driver. This crash type is characteristic of driver inattention and situations where the first several parts of a complicated maneuver are successfully completed only to have a "failure" at or near the end of the decision sequence. Older drivers seemed especially prone to this sort of problem. Similarly, the driver who hits the turning driver is typically taken by surprise by an unexpected maneuver. The situation provides some insight into how drivers, and especially older drivers, respond to complex and unexpected situations—poorly.

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

- *Problems with recognition/non-recognition of traffic signals*: Another common problem with older drivers, which would typically result in an angle crash, was an apparent difficulty in noticing red traffic signals. Anecdotal comments included the older driver not remembering what color the signal had been—presumably either because they did not see it, did not interpret its message correctly, or simply lost the cue amongst the other visual information. While drivers from all ages are guilty of such infractions, they did seem to come up frequently when the older driver was considered. Conversely, when older drivers recognized and stopped (appropriately) for a signal, they were sometimes victims in rear-end crashes—e.g., they stopped for a red light only to be rear-ended by the following driver (who was, more often than not, a younger person).

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

- *Inappropriate use of turning lanes or turns from incorrect lanes:* A considerable number of crashes occurred because the older driver failed to use a lane correctly. There were several variations on this problem: a two-way left-turn lane (TWLTL) was not used for turning at all; the TWLTL was entered too far in advance of where the turn was to be made; right turns were inappropriately made from a non-curb through lane; and, left turns were made from the right (curb) lane. Other turning crashes occurred simply because the older driver ignored turning movement restrictions (e.g., turned left when left turns were prohibited).

- *Median U-turn crashes*: On boulevards, a fairly common technique used in Michigan to avoid left turns at high volume intersections is to have would-be left-turning vehicles go through an intersection and use a median crossover to reverse directions, and then make a right turn (e.g., an eastbound driver that wishes to turn north at an intersection continues eastbound through the intersection, uses a crossover to reverse directions to the west, and then turns right [north]). In the several crossover crashes that were reviewed, the older driver was invariably at least partially at fault. They generally misjudged the maneuver and their vehicle's position with respect to proximity to other vehicles in the crossover itself or crashed with other vehicles upon leaving the crossover area. While the crossover maneuver is not an easy one to accomplish, nor necessarily widely used elsewhere, the crashes at such locations tend to provide for some insight into the problems that older drivers have with this and other types of channelization. The use of channelization requires an additional load in terms of vehicle control (i.e., a lower margin of error in lane selection and use).

- *Vehicle alignment and guidance problems—left turns*: Another class of problems for older drivers in intersections relates to misjudging of distances in general, where the vehicle is with respect to placement in the travel lanes, and where the vehicle is in relation to other vehicles.

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

  Another crash outcome with the same turning scenario has the older driver turning left and "clipping" the vehicle in the lanes to the driver's immediate left (e.g., a driver making a northbound to westbound left turn would "clip" eastbound drivers waiting for the signal to change). This was noted as a problem that was not exclusively one of older drivers. There were several potential causes of this sort of crash: the turning driver was "hurried" by oncoming drivers and turned short to avoid them; the waiting vehicle was beyond the stop line; and the driver simply misjudged the positions of their and other vehicles. Finally, older drivers also seem to be prone to make misjudgments in using right- and left-turn lanes (or flares). There were several instances when older drivers who were attempting to move into the turning lanes collided with vehicles that were already in the lane (e.g., in the older driver's "blind spot"). This same sort of problem is likely with the older driver moving from the flare or terminating lane to the adjacent through lane.

These three crash types all occur in intersections which are complex. They have multiple lanes, mixed use of lanes, relatively large distances that need to be traversed to complete maneuvers, complex signalization, and numerous conflicting maneuvers being performed by other vehicles. Thus, task demands and older driver abilities are not well matched at intersections requiring quick, accurate decisions and smoothly executed maneuvers.

- *Vehicle alignment and guidance problems—right turns*: Another class of turning crashes in which older drivers seem to be overinvolved is the right-turning vehicle "swinging wide" out of the curb lane and encroaching on the next lane over. This is a combination of controlling the vehicle's path and misjudging the proximity of vehicles in adjacent lanes, and could occur at any intersection. At other right-turn locations the addition of a flare for the right-turning drivers to use as an acceleration lane allows the driver some space to accelerate during the turning maneuver. There are however, some potentially negative aspects to this sort of treatment: turning drivers may not stop at all and simply assume that they have a "free on-ramp" which does not require them to merge; some drivers will be forced into a situation requiring them to "look over their shoulder" which may be physically difficult to accomplish; and they are more likely to be required to perform a true merging maneuver which generally seems to present problems for older drivers.

Convergent evidence of unsafe behaviors by older drivers is provided in a study by McKnight and Urquijo (1993), who examined the criteria that law enforcement personnel use when referring older drivers for reexamination, following their observations of signs of incompetence when an older driver is stopped for a violation or is involved in a crash. The data consisted of 1,000 police referral forms from the motor vehicle departments of California, Maryland, Massachusetts, Michigan, and Oregon. Referrals were classified on the basis of initial contact, as well as the behaviors leading to the contact and the deficiencies that served as the basis of referral. Initial contact could result from one of four conditions: a crash, a violation, police observation of aberrant behavior, or referral by an outside source such as friends, relatives, or physicians. Of particular interest in this project are the specific behaviors contributing to the contact between the aging driver and the police officer which may be of significance at intersections. These included: driving the wrong way or on the wrong side of the street; driving off the road; rear-ending a vehicle; failing to yield the right-of-way or come to a complete stop at a stop sign; infringing on the rights of a pedestrian or cyclist; turning across the path of oncoming vehicles; crossing lane markings; operating at low speed; and other behaviors.

Results of the data analysis showed that older driver crashes were the leading source of referrals (48 percent), followed by violations (44 percent). Observed behavior accounted for 7 percent of the referrals and outside referrals accounted for only 1 percent. The primary behaviors that brought these drivers to the attention of police were: driving the wrong way on a one-way street or on the wrong side of a two-way street, which contributed to many violations (149), but few crashes (29) and accounted for 19 percent of the referrals; driving off the paved surface, which contributed to many crashes (176) but few violations (8) and accounted for 19 percent of the referrals; and failing to stop or yield to other traffic, which contributed to significant numbers of crashes (74) and violations (114), and accounted for 18 percent of the referrals. Making unsafe turns in front of other traffic was half as frequent as the three aforementioned behaviors, but is a mistake in which older drivers are generally overrepresented; turning across traffic contributed to 46 crashes and 43 violations, or approximately 9 percent of the referrals. Other contributing behaviors, in decreasing frequency, included: driving very slowly; rear-ending another vehicle; backing improperly; failing to observe lane markings; and not yielding to pedestrians and bicyclists.

Also of interest is a study by McKnight and Stewart (1990), which identified competencies critical to the safety and mobility of the driving public in a project sponsored by the California Department of Transportation. In this research, mismatches between specific driver groups and performance requirements were identified through literature review, crash analysis, consultation with experts, and results of written and drive tests, in an effort to group competencies required for four stages of licensing (pre-licensing, new licensing, renewal licensing, and remedial licensing). Of greatest interest in the present research are the competencies evaluated with respect to remedial licensing (of older drivers), with an emphasis on those that are critical to the safe and effective negotiation of intersections. These competencies are noted below, with indications of their presumed relationships to the problem behaviors of older drivers.

- *Lane keeping*: The ability to keep the vehicle positioned in the lane, by relating speed and position inputs to steering outputs was rated as a critical competency. According to McKnight and Stewart (1990), difficulty in lane keeping is characteristic of older drivers, and results in frequent lane exceedences. (See also Szlyk, Brigell, and Seiple [1993], who found in a simulator study that driver performance for lane keeping was significantly compromised in a group of older patients with visual field losses; variability in lane position was also predictive of real-world crashes.)

- *Basic lane use*: The proper use of lanes is critical to all traffic maneuvers. On-road driving evaluations in an occupational therapy setting include frequent reports of older clients making turns from the wrong lane[3].

- *Turning*: Positioning a vehicle in preparation for turning was identified as a critical competency. The cited difficulties with this behavior result from drivers who, with diminished limb strength, swing too wide in order to lengthen the turning radius and thus minimize rotation of the steering wheel.

- *Slowing/stopping*: Anticipating the need to stop well in advance is critical to safety, especially in heavy traffic where sudden stops disrupt the flow of traffic and increase the likelihood of rear-end collisions. Related work by Szlyk et al. (1993) has indicated that average stopping times for normally sighted older drivers and those with visual

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

field loss were prolonged when compared to normally sighted young subjects in a driving simulator study. In addition, those subjects who had been involved in real-world crashes generally had longer stopping times. Also, on-road driving assessments in a rehabilitation setting have documented older drivers frequently exhibiting difficulties in estimating closing distances, requiring them to brake hard at the end of a slowing maneuver to avoid hitting the vehicle stopped ahead of them[4].

Once stopped at an intersection, maintaining brake pressure becomes critical to avoid crashes within a queue, and because of its importance in preventing the car from being pushed into the vehicle ahead if struck from behind. A driving simulator study found that older drivers (both normally sighted controls and patients with visual field loss) produced greater variability in brake pressure when compared to younger, normally sighted subjects (Szlyk et al., 1993).

- *Search and scanning behaviors*: Consistent with other analyses, the category of behavior pinpointed by McKnight and Stewart (1990) as most involved in crashes was *search*. Maintaining general surveillance is critical to safety, as evident in the fact that "improper lookout" has been identified as the leading behavioral contributor to crashes (Treat, Tumbas, McDonald, Shinar, Hume, Mayer, Stansifer, and Castellan, 1977). A critical element of "proper lookout" is fixating far enough ahead—approximately 10 to 15 seconds—to be able to anticipate problems and to adjust to path obstructions without abrupt maneuvering. Although older, generally more experienced drivers do a better job of "distance scanning" than young, inexperienced drivers (Mourant and Rockwell, 1972), their slower reflexes and decreased visual ability means that they need more space and time to react to roadway/traffic situations. The increased rate of lane exceedences for older drivers noted by McKnight and Adams (1970) may be related to a deficiency in search of the roadway downstream.

  Search to the sides and rear of the vehicle is also a critical competency for safe lane changes and merging with traffic. On-road assessments with clinical populations have found that older patients have difficulty in searching and scanning: they don't always know where and when to look, and often fail to look over their shoulders and in their mirrors before changing lanes[5].

  Slowed visual scanning of traffic on the intersecting roadway by older drivers also has been cited as a cause of near misses of (crossing) crashes at intersections during on-road evaluations. In the practice of coming to a stop, followed by a look to the left, then to the right, and then back to the left again, the older driver's slowed scanning behavior allows approaching vehicles to have closed the gap by the time a crossing maneuver finally is initiated. The traffic situation has changed when the older driver

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[4] Personal communication, Sue Henderson, Driver Rehab Services, Memorial Hospital, South Bend, IN, 3/11/94.

[5] Personal communication, Sue Henderson, Driver Rehab Services, Memorial Hospital, South Bend, IN, 3/11/94.

actually begins the maneuver, and drivers on the main roadway must adjust their speed to avoid a collision[6].

Next, this review must acknowledge the efforts of Malfetti and Winter (1987) to comprehensively document the unsafe driving behaviors exhibited by older drivers. The purpose of this study was to determine what experts in the fields of driver licensing, traffic safety, driver education and training, enforcement, and gerontology as well as older drivers themselves considered indicative of "safe" and "unsafe" driving behavior of older drivers. A critical incident technique, where experts describe actions of older drivers that they have observed or in which they participated, yielded 1,838 descriptions to paint a picture of the performance of drivers age 55 and older. The following paragraphs highlight only those critical unsafe behaviors relating most obviously to intersection negotiation.

Unsafe driving practices included: failing to position the car correctly for turning or turning from an improper lane or at an improper time or pace at intersections (particularly for left turns); lane straddling; weaving; changing lanes without signaling; unsafe actions at stop signs; failure to respond properly to road signs and signals; and inattention to driving.

Lane-use behavior was a category in which there were substantially more unsafe descriptions than safe descriptions. Unsafe behaviors included: using a turning lane for passing; driving on the wrong side or in the middle of the road; and driving into the lane of opposing traffic. Descriptions of left-turn behavior were overwhelmingly unsafe, such as turning from the wrong lane; turning too sharply or widely; turning suddenly but progressing slowly; and positioning the car so it blocked oncoming traffic or the intersection after a signal change. Unsafe left turns at complex or four-way crossing intersections were revealed in some of the critical incidents; however, unsafe behaviors were also described for left turns at less complicated intersection configurations as well. Unsafe right-turning behaviors included: swinging too wide before turning; turning too short or sharply and jumping the curb or road edge; turning from the wrong side of the road or from an incorrect lane position; and encroaching on the oncoming lane of traffic after a turn.

Use of brakes was a category that generated only unsafe descriptions, which consisted mainly of excessive braking. Excessive braking is confusing and disruptive to following traffic, as is suddenly jamming on the brakes for no apparent reason and/or whenever a road sign or signal is sighted. There were many descriptions of older drivers who stopped at unexpected times and in unexpected places. In particular, they stopped suddenly without warning, or stopped approximately 12 m (40 ft) ahead of an intersection or in the intersection.

Failing to respond properly or respond at all to road signs and signals was also a frequently described unsafe behavior. There were many descriptions that included running a red light or stop sign, or rolling through a stop sign. Some older persons' behavior at stop signs and signals seemed to indicate that they didn't understand why they needed to wait

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

when no other traffic was coming. Additionally, stopping at a green light for no apparent reason, and going the wrong way on a one-way street were also frequently observed unsafe behaviors. At complex intersections, unsafe performance seemed due to ignorance of the rules of the road which can vary from place to place. Also not knowing how far to pull into the intersection while awaiting a chance to turn and knowing how many cars can/will turn during the caution phase appear to cause problems for older drivers making go/no-go decisions at intersections.

Entering traffic from a side road without adequate search, and then entering the stream of traffic either too fast or too slow and interfering with traffic already on the roadway were also identified as unsafe behaviors. Even when older drivers searched all directions, they displayed confusion with signals given by other drivers, which added to their difficulties yielding to other traffic. Failing to yield the right-of-way to pedestrians was an often reported unsafe behavior.

Driving too slowly (e.g., driving 32 km/h [20 mi/h] in a 72 km/h [45 mi/h] zone), and impeding the traffic flow was mentioned frequently as an unsafe driving behavior. Although it is a self-correcting behavior for drivers who have difficulty processing multiple sources of stimuli with diminished visual and perceptual capabilities, it often leads to other drivers performing unsafe behaviors, such as passing in unsafe places or at unsafe times.

Finally, a discussion of perceived difficulties with intersection negotiation by older drivers themselves, and the reasons for such difficulties, provides an important complement to the results of analyses reported above.

To begin, interviewees in the Milstein and Gutman (1988) focus group were asked about which driving maneuvers were most difficult to perform. Making a left turn at an uncontrolled intersection was "frequently difficult" or "sometimes difficult" for 23.7 percent of the sample. The percentage of drivers reporting difficulty with this maneuver increased as age increased; 21.4, 23.3, and 28.2 percent of the drivers ages 55-64, 65-74, and 75 and older, respectively, responded in this manner. A higher percentage of the older females reported difficulty than males. Entering and crossing an uncontrolled intersection was regarded as less of a problem, with 16.8 percent of the sample responding that they "sometimes" or "frequently" encountered difficulty. For this maneuver, 15.8, 17.3 and 16.6 percent of the drivers ages 55-64, 65-74, and 75 and older, respectively reported difficulty either "frequently" or "sometimes." Again, a higher proportion of females reported difficulty than did the males.

In an effort to analyze the needs and concerns of senior drivers, the Illinois Department of Transportation sponsored a statewide survey of 664 drivers, followed by focus group meetings held in rural and urban areas (Benekohal et al., 1992). Given the sample size, the following four age categories were used to provide reliable statistical analyses: ages 66-68; ages 69-72; ages 73-76; and age 77 and older. Respondents were asked to indicate whether specific driving situations had become more difficult now as compared to 10 years ago. Additionally, they were asked to indicate how important highway design features have become in driving safely now as compared to 10 years ago.

With regard to intersections, Benekohal et al. (1992) found that the following activities have become more difficult for seniors (with proportion of drivers responding in parentheses): driving across an intersection (21 percent); finding beginning of a left-turn lane at an intersection (20 percent); making a left turn at an intersection (19 percent); following pavement markings (17 percent); responding to traffic signals (12 percent), and reading street signs in town (27 percent). The highway features that have become more important to drivers (with proportion of drivers responding in parentheses) are: lighting at intersections (62 percent); pavement markings at intersections (57 percent); number of left- turn lanes at intersection (55 percent); width of travel lanes (51 percent); concrete lane guides for turns at intersections (47 percent); and size of traffic signals at intersections (42 percent).

Comparisons of responses from the drivers ages 66-68 and 77 and older showed that the older group had more difficulty following pavement markings, finding the beginning of the left-turn lane, driving across intersections, and driving in the daytime. Similarly, the level of difficulty for reading street signs and making left turns at intersections increased with increasing senior driver age. Turning left at intersections was perceived as a complex driving task, made more difficult when channelization providing visual cues was absent, and only pavement markings designate which lane ahead is a through lane and which is a turning lane. The cognitive process of lane location detection and selection must be made upstream at a distance where a lane change can be performed safely. Late detection by older drivers will result in lane weaving close to the intersection, a behavior for which older drivers exhibited difficulties, as mentioned in the previous section. Also in the case of channelized dual left-turn lanes, maintaining lane position without conflict is complex and uncertain for many drivers, but particularly so for senior drivers. For the oldest age group, pavement markings at intersections were the most important item, followed by the number of left-turn lanes, concrete guides, and intersection lighting.

Respondents in the focus group discussions (Benekohal et al., 1992) reported that intersections with too many islands are confusing because it is hard to find which island the driver is supposed to go around. Raised curbs that are unpainted are difficult to see, especially in terms of height and direction, and result in people running over them. Older drivers preferred to have rumble strips in the pavement to warn them of upcoming concrete medians, that they are approaching a signal, and to warn them of getting too close to the shoulder. Surprisingly, two way left-turn lanes did not seem to be confusing to the participants, although they were bothered by the fact that other drivers use these lanes for passing.

Regarding traffic signals, older drivers indicated that the green time is too short, and that in general, they needed more time to react. They prefer to turn left at intersections that contain a protected arrow phase, rather than making "permitted phase" left turns. When turning during a permitted phase (green ball) signal operation, older drivers reported that they wait for a large gap before making a turn; this appears to frustrate following drivers and causes the following drivers to go around them or blow their horns.

Older drivers' perceptions of the problems they experience in the use of intersections has also been explored by Staplin et al. (1997). Eighty-one older drivers, including 46 drivers ages 65-74 and 35 drivers ages 75 and older were assembled in 11 discussion groups of 6-8 drivers each to report on specific areas of difficulty. Responses were rank-ordered in terms of subjective importance to the older group participants. This was done according to the frequency of mention and the degree of agreement with which a comment was received by a group. A summary of identified problems at intersections associated with specific driver behaviors is presented below, in descending order of subjective importance:

- Difficulty in turning head at angles varying from 90° to view traffic on intersecting roadway.

- Difficulty in smoothly performing turning movements at tight corners.

- Hitting raised concrete barriers such as channelizing islands in the rain and at night due to poor visibility.

- Finding oneself positioned in the wrong lane—especially a "turn only" lane—during an intersection approach due to poor visibility of pavement markings or obstruction of roadside signs which are designed to warn motorists of traffic patterns at the intersection.

- Difficulty in seeing potential conflicts well and quickly enough to smoothly merge with adjacent lane traffic at the end of an acceleration lane, after making a right turn.

- Merging with adjacent lane traffic when a lane drop (e.g., two lanes into one) occurs near the intersection (e.g., within 152 m [500 ft]).

- Lane keeping and avoiding sideswipe crashes when using dual left-turn lanes.

- Merging with adjacent lane traffic in a dual left-turn situation when a lane drop occurs after the turn.

Parenthetically, a cautionary note concerning the *rate* of self-reported unsafe behaviors by older drivers at intersections is justified by the responses of participants in the Milstein and Gutman interviews (1988), who were asked to report what they believed to be their most frequent driving fault. It may be remembered that older drivers have been most often cited with failure-to-yield and disobeying a traffic signal in comparison to groups of middle-aged drivers (e.g., Council and Zegeer, 1992; Cooper, 1990; Staplin, et al., 1992). However, only 1.4 percent of the 904 drivers age 55 and older in the Milstein and Gutman study (1988) reported that their most frequent driving fault was failure-to-yield. Breaking down their responses by age group, the percentages of drivers responding that their most common driving error is failure-to-yield were 0.5, 1.8, and 2.0, for drivers ages 55-64, 65-74, and age 75 and older, respectively. This points to a discrepancy in what older drivers perceive about their driving performance, compared with what is actually occurring at intersections. It is also possible that the individuals experiencing intersection crashes are not well represented in the older drivers sampled in self-report studies.

To conclude this section, a summary listing of specific unsafe behaviors at intersections which, according to previously-cited work, occur with increasing frequency among the older driver population is presented in Table 7.

Table 7. Unsafe driving behaviors performed by older drivers at intersections.

Unsafe behaviors related to signs and signals	Unsafe behaviors in lane use	Unsafe behaviors during turns	Unsafe vehicle control behaviors	Unsafe behaviors when reacting to traffic

• disregard for yield sign
• running stop signs
• rolling through a stop sign
• proceeding without clearance after stopping at a stop sign
• poor vehicle positioning at stop signs
• jerky/abrupt stops
• running red lights
• running amber lights
• proceeding through an intersection on a green light without verification that the intersection is clear
• stopping at green lights
• lack of enough caution at traffic lights
• failure to understand signs
• blocking oncoming traffic in the middle of an intersection after the signal has changed
• braking every time a sign or signal is sighted
	• lane straddling
	• failure to check blind spot when changing lanes
	• use of a turning lane for passing
	• cruising in the passing lane
	• choosing the incorrect lane for turning or through maneuver
	  • making left turn from a center (through) lane or curb (through or right) lane
	  • making right turn from a non-curb through lane
	  • continuing through the intersection in a turn-only lane
	• center two-way left-turn lane not used at all for turning
	• center two-way left-turn lane entered too far in advance of turn
	• driving on the wrong side of the road
	• going the wrong way on a one way street
	• failure to observe lane markings
	• unsafe gap acceptance when changing lanes
		• failure to signal intention to turn
		• signaling too early or too late
		• unsafe gap acceptance when turning left (head-on opposing conflict vehicle)
		• unsafe gap acceptance when turning right (conflict vehicle approaching at 90 ° from left)
		• unsafe gap acceptance when crossing
		• entering the wrong lane on the receiving leg of an intersection
		• swinging too wide when turning
		• turning too short and "clipping" a vehicle on the left, or hitting the curb on the right
		• turning into a lane of opposing traffic
		• turning suddenly and accelerating slowly after the turn
		• turning where turns are prohibited
		• exceeding lane boundaries during turns
			• excessive braking
			• jamming on the brakes for no apparent reason
			• delayed braking at intersections and crosswalks
			• applying the accelerator instead of the brake
			• putting the car in the wrong gear
			• activating the wrong turn signal
			• driving with both brake and accelerator depressed
				• failure to yield
				• following too closely
				• unnecessary and unexpected stopping in traffic (braking unsafely)
				• driver inattention
				• failure to maintain adequate distance vision ("improper lookout")
				• performing a maneuver while being waved on by another driver, without regard for other traffic or traffic control
				• interfering with the traffic flow by entering too fast or too slow
				• driving too slowly
				• looked but did not see potential conflict vehicles/did not look
				• delay in decision making and maneuver initiation
				• seeing a car coming but unable to respond
				• panicking when emergency vehicles approach

A TASK ANALYSIS TO PRIORITIZE OLDER DRIVERS' PROBLEMS AT INTERSECTIONS

The concluding activity performed to identify intersection negotiation problems of older drivers was a limited task analysis. This activity drew upon earlier efforts (cf. McKnight & Adams, 1970), modified to address performance demands on drivers in carrying out each principal intersection maneuver—left turn, right turn, and through/crossing movement—under *all* pertinent sign and signal conditions for traffic control across a range of very specific features and geometries encompassing the overwhelming majority of intersection types found in the U.S. (American Association of State Highway and Transportation Officials [AASHTO], 1990). This analysis was limited in the sense that it was confined to intersection negotiation problems arising specifically out of the interaction of maneuver task requirements and age-related functional deficits, and does not address all potential problems encountered by drivers regardless of age nor by older drivers regardless of maneuver. The conclusions reported in this section are thus derived from the formal analysis of: (1) the demands associated with specific task elements, for safe performance under defined operating conditions; and (2) the known psychophysical deficiencies of older drivers, as highlighted earlier in this report.

In the following pages this section presents: (1) a specification of task parameters; (2) an identification of performance demands; (3) the underlying assumptions and the procedures for generating ratings of relative error and crash likelihoods, taking into account mismatches resulting from older driver deficiencies; and (4) conclusions and a prioritization of older driver intersection negotiation problems.

SPECIFICATION OF TASK PARAMETERS

Maneuver tasks in this analysis were specified according to cells within a three-dimensional matrix consisting of 17 intersection *types* that are defined primarily by the number of lanes and lane assignments, 3 *directions* of motion (through, left-, and right-turn) to describe the driver's intention at the intersection, and 10 traffic *controls*, i.e., signs or signal phases of an intersection traffic control device. While such a matrix should give rise to 510 different tasks, the actual number of tasks was constrained by the absence of certain combinations of motion and traffic signs/signals (e.g., response to directional arrows when driving straight through an intersection), and the fact that even those combinations that arise at one intersection may not arise at another. A list of the key defining movements and traffic control operations follows in Table 8, and Figure 4 presents the actual matrix of intersection type by movement by traffic control status considered in the task analysis. Plan view drawings of the 17 intersection types are included in Figures 5 through 21.

Table 8. Key to intersection maneuvers by operation considered in performance of task analysis.

	Signal Phase or Sign	Movement
A	Green (steady arrow or ball)	Through
B	Flashing red ball	Through
C	Flashing yellow ball	Through
D	Steady yellow ball	Through
E	Stop sign (own direction)	Through
F	Stop sign (all way)	Through
G	Steady green arrow	Left Turn
H	Steady green ball	Left Turn
I	Flashing red ball	Left Turn
J	Flashing yellow ball	Left Turn
K	Steady yellow ball	Left Turn
L	Steady yellow arrow	Left Turn
M	Stop sign (own direction)	Left Turn
N	Stop sign (all way)	Left Turn
O	Steady green arrow	Right Turn
P	Steady green ball	Right Turn
Q	Steady red ball	Right Turn
R	Flashing red ball	Right Turn
S	Flashing yellow ball	Right Turn
T	Steady yellow arrow	Right Turn
U	Steady yellow ball	Right Turn
V	Stop sign (own direction)	Right Turn
W	Stop sign (all way)	Right Turn
X	Yield sign	Right Turn

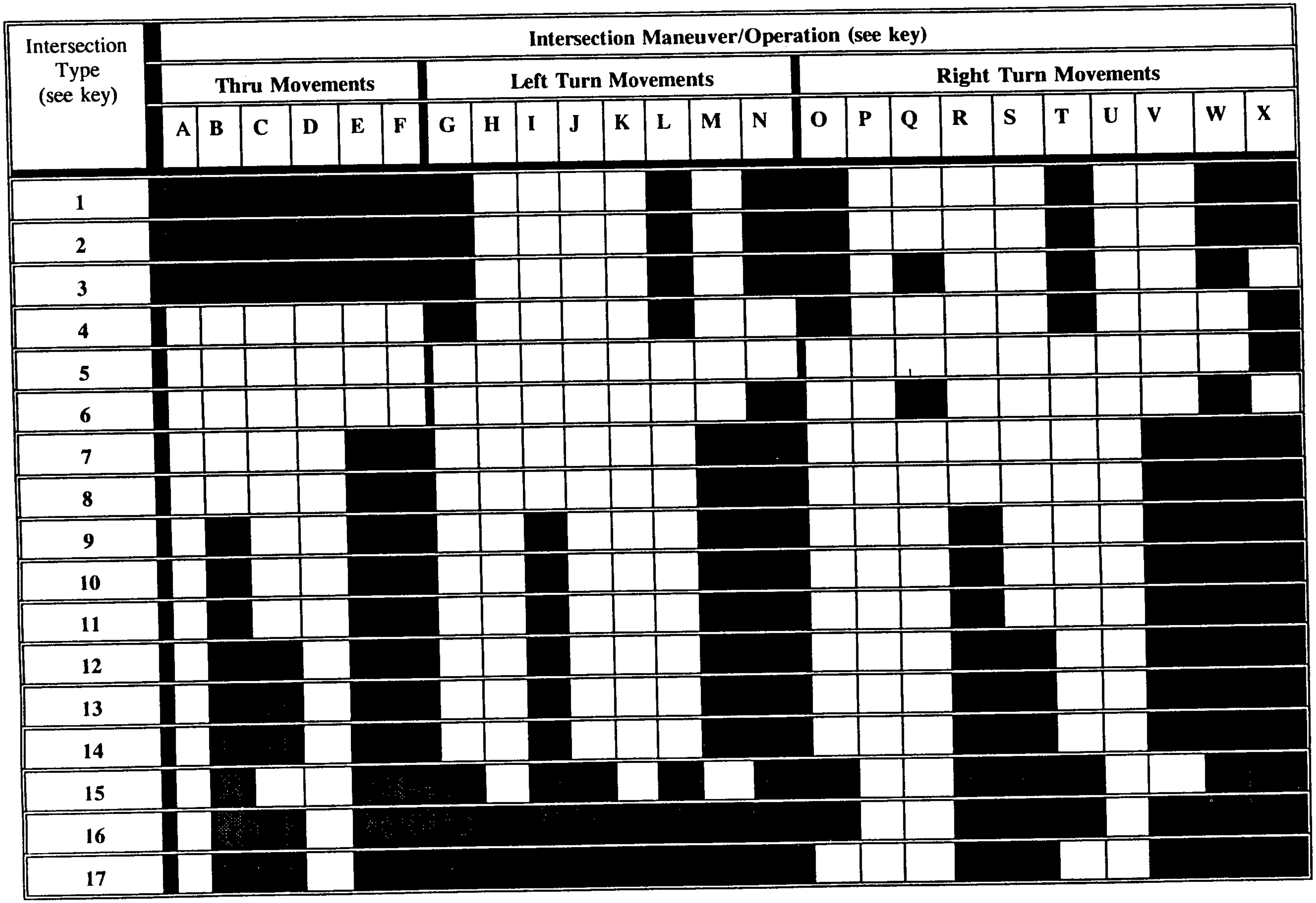

Figure 4. Matrix defining conditions for which task analysis was performed.
(NOTE: Shaded cells denote conditions excluded from analysis).

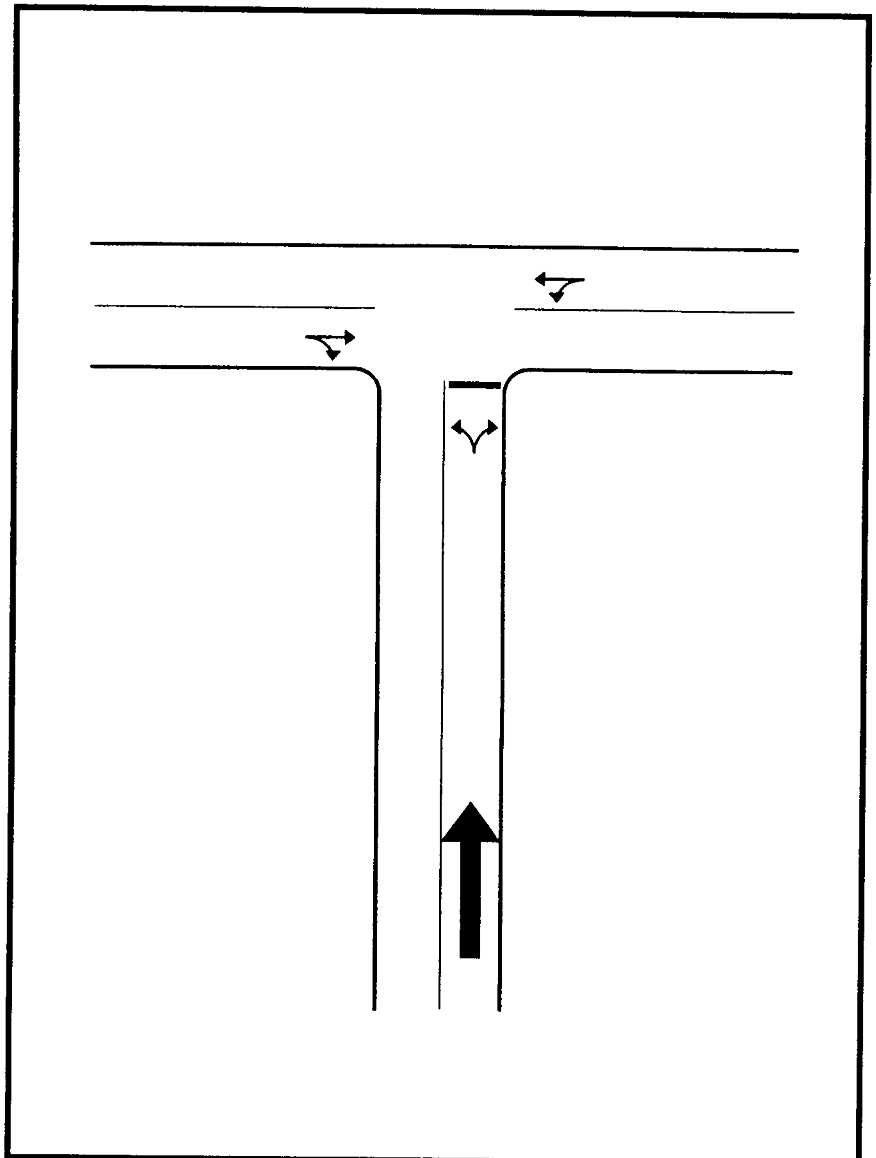

Figure 5. Intersection type 1: 2-lane by 2-lane T-intersection with no auxiliary lanes.

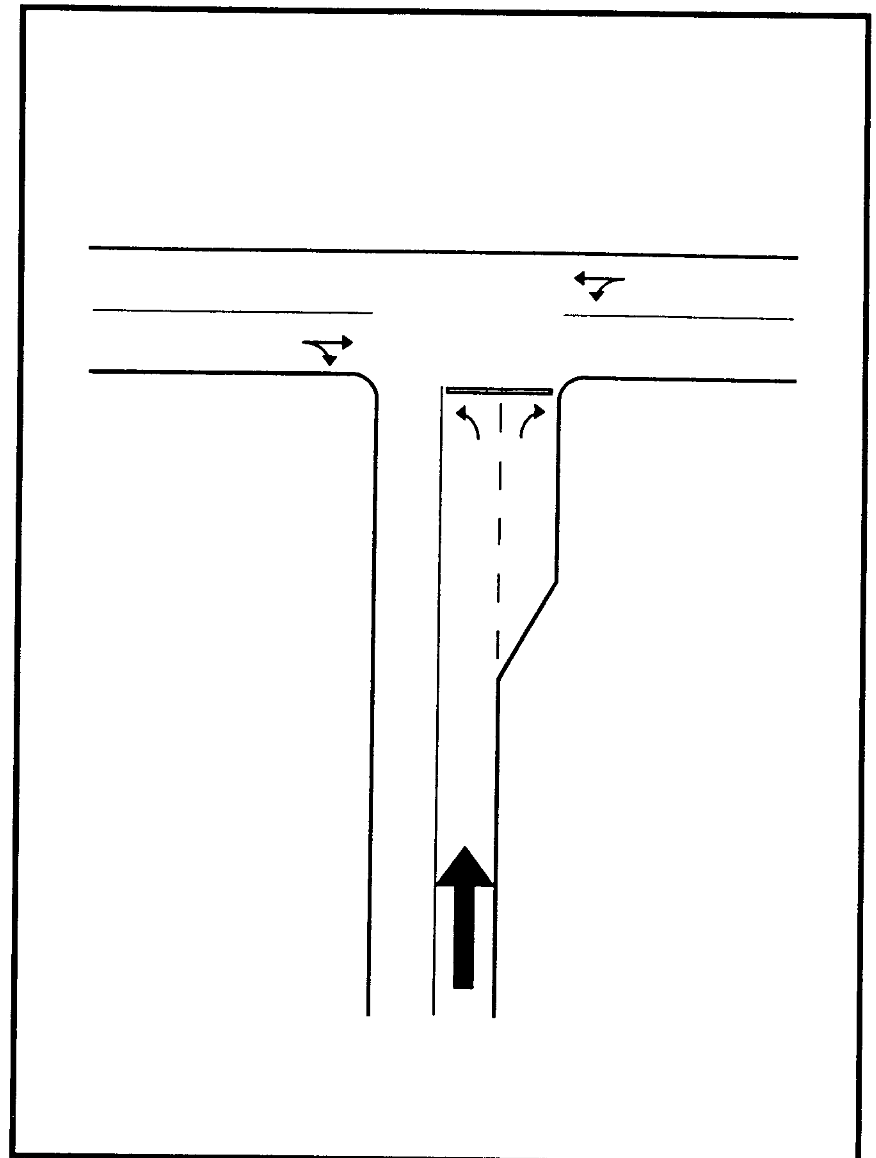

Figure 6. Intersection type 2: 2-lane by 2-lane T-intersection with right-turn-only lane.

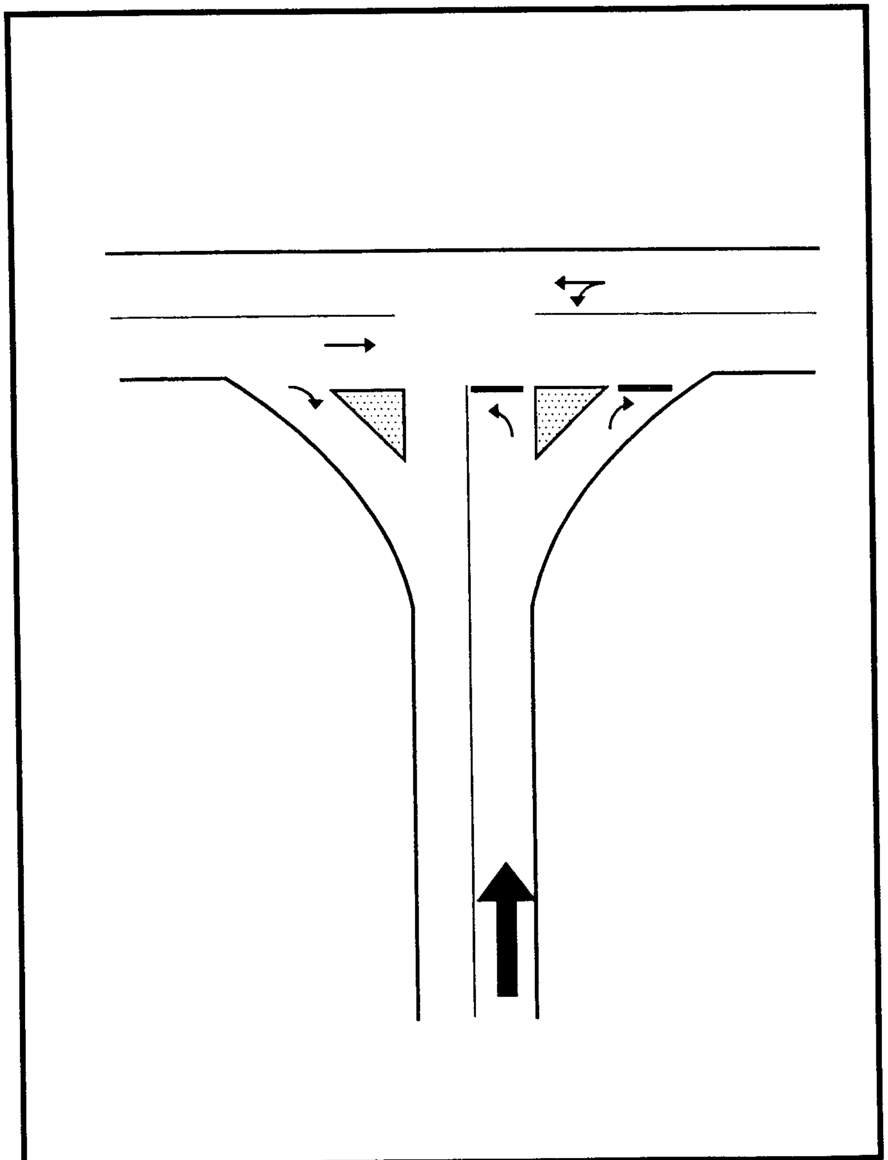

Figure 7. Intersection type 3: channelized 2-lane by 2-lane T-intersection.

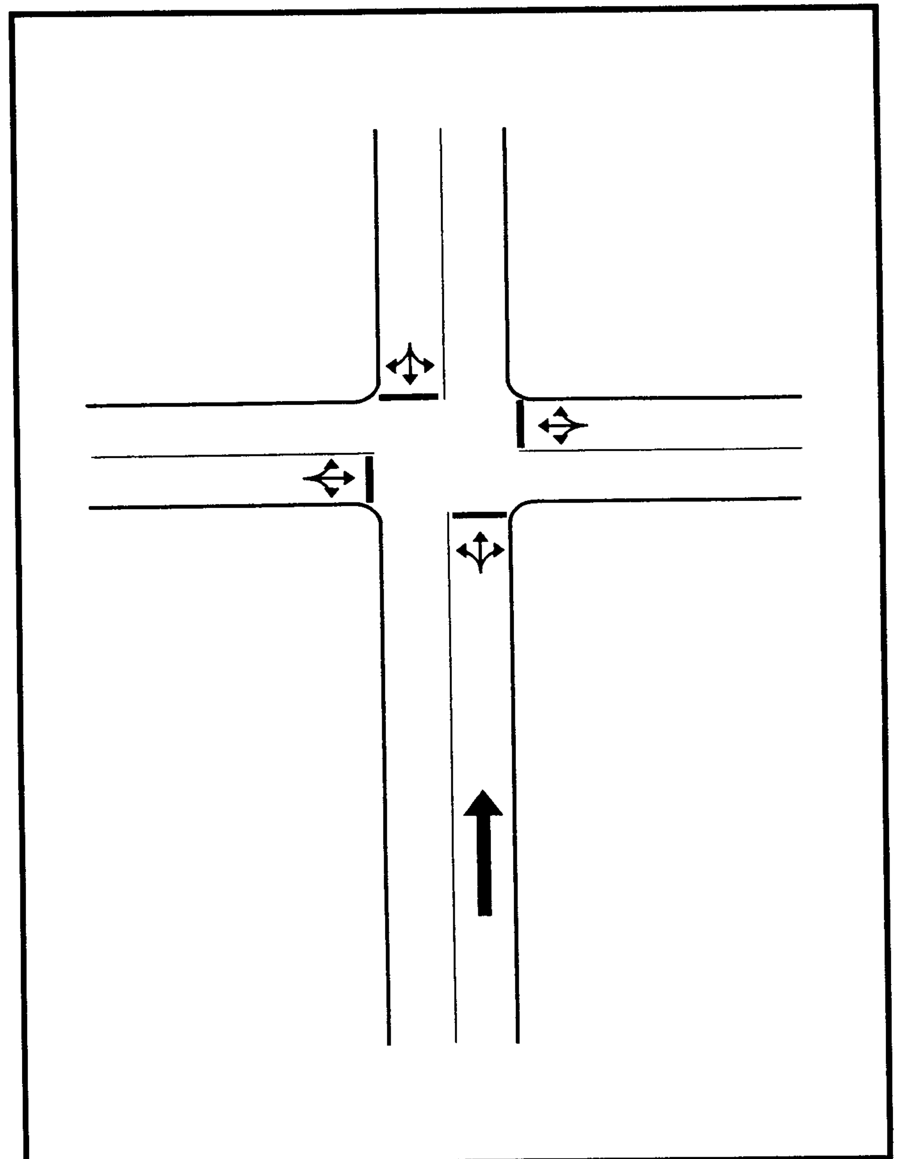

Figure 8. Intersection type 4: 2-lane by 2-lane roadway with no auxiliary lanes.

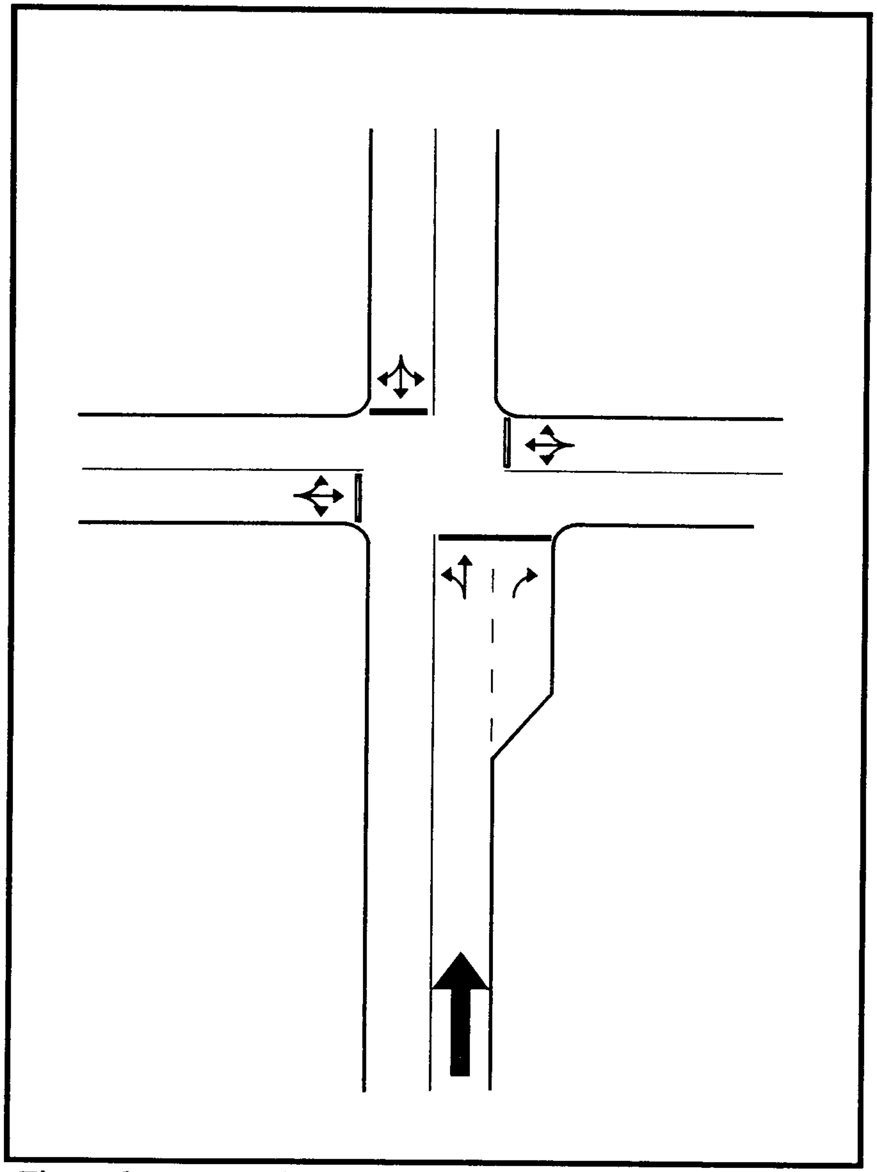

Figure 9. Intersection type 5: 2-lane by 2-lane roadway with right-turn lane.

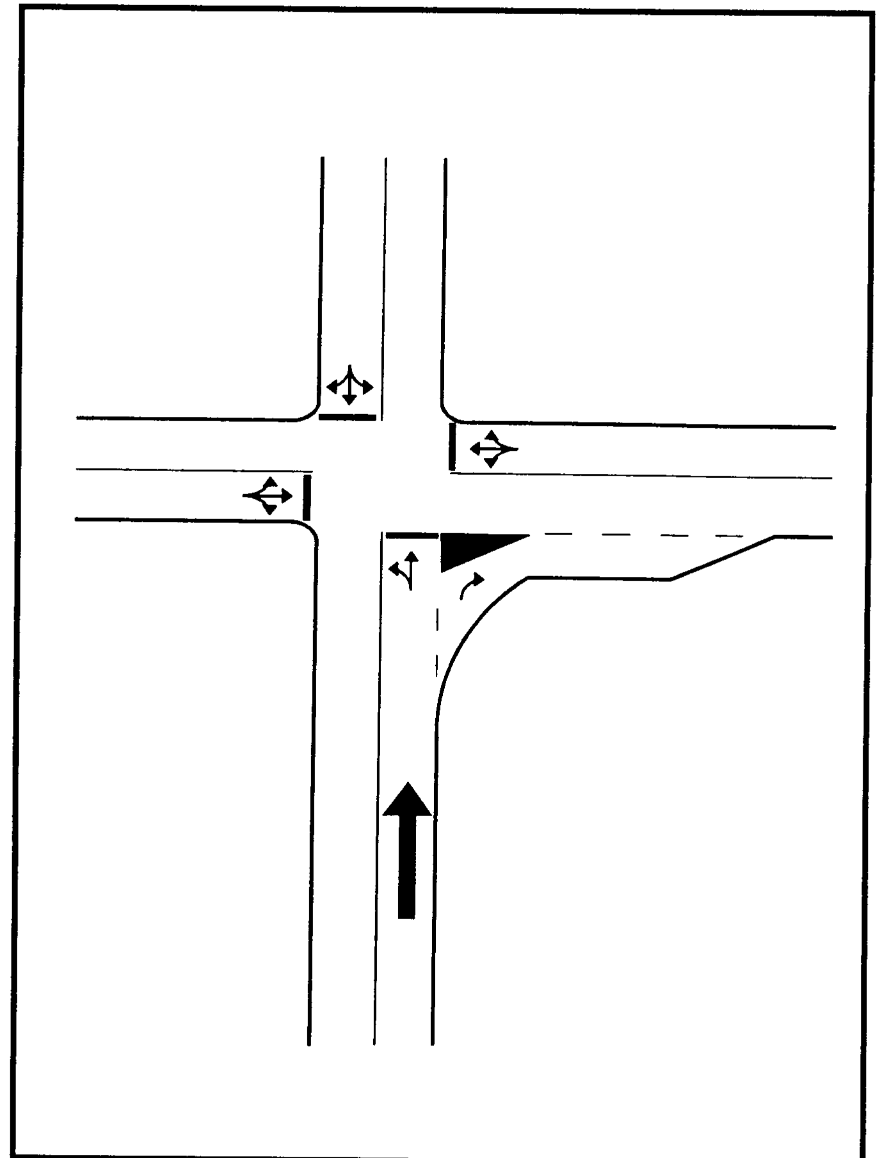

Figure 10. Intersection type 6: 2-lane by 2-lane roadway with channelized right-turn lane and acceleration lane.

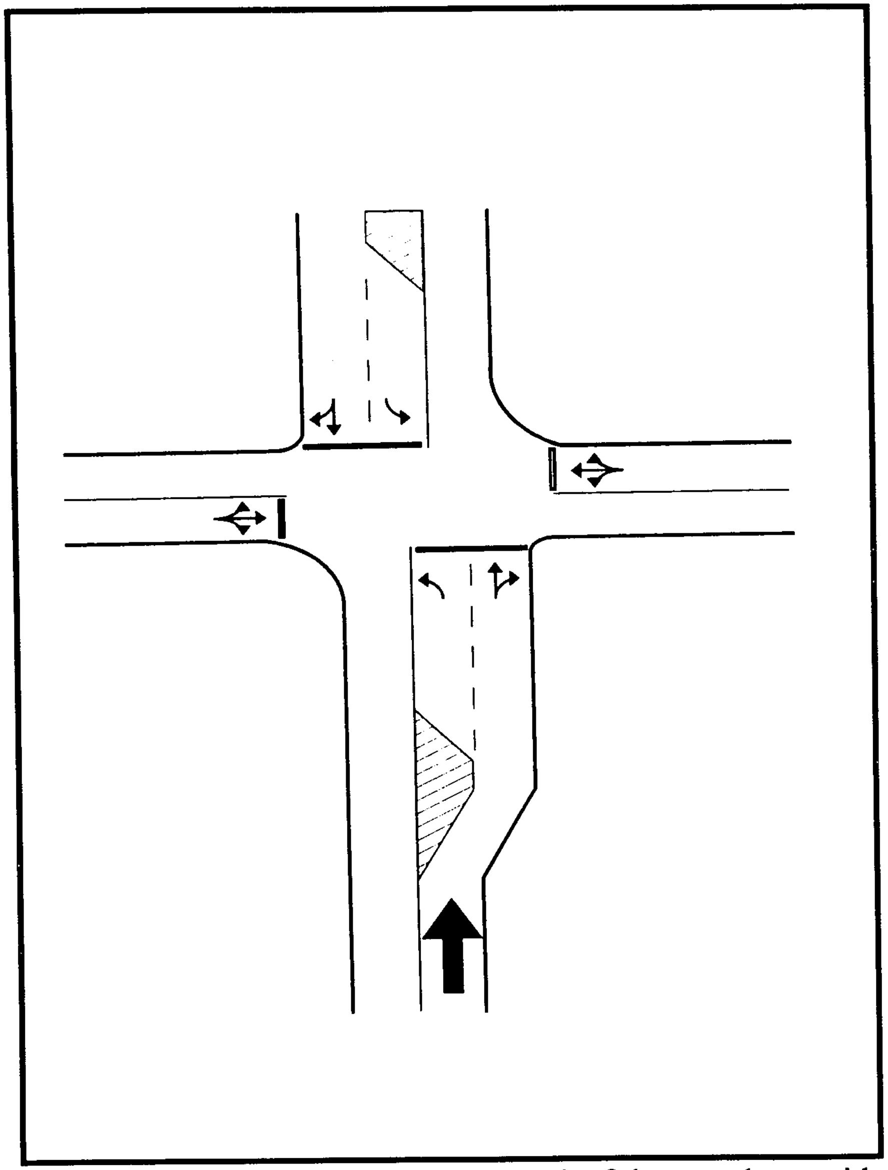

Figure 11. Intersection type 7: 2-lane by 2-lane roadway with opposing left-turn lanes and misalignment.

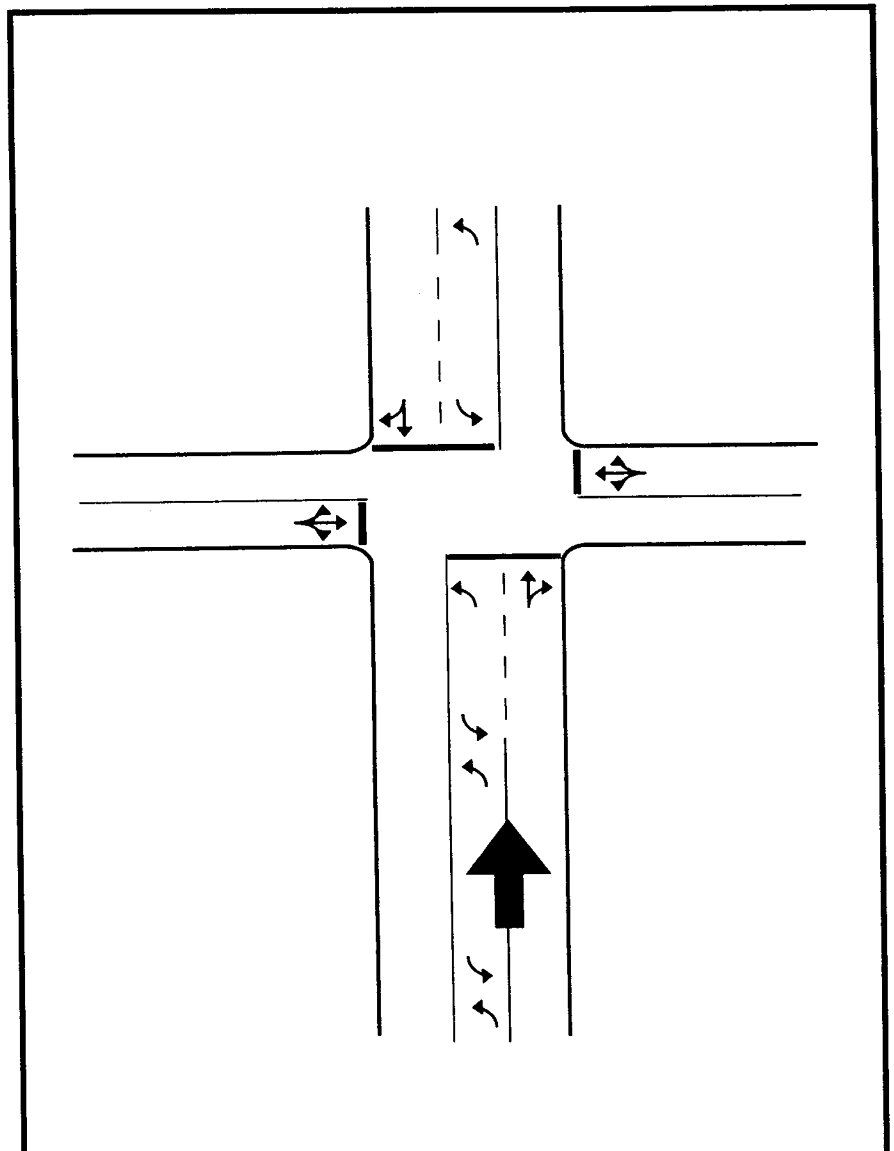

Figure 12. Intersection type 8: 2-lane roadway with opposing left-turn lanes and two-way left-turn lane approach, by 2-lane roadway.

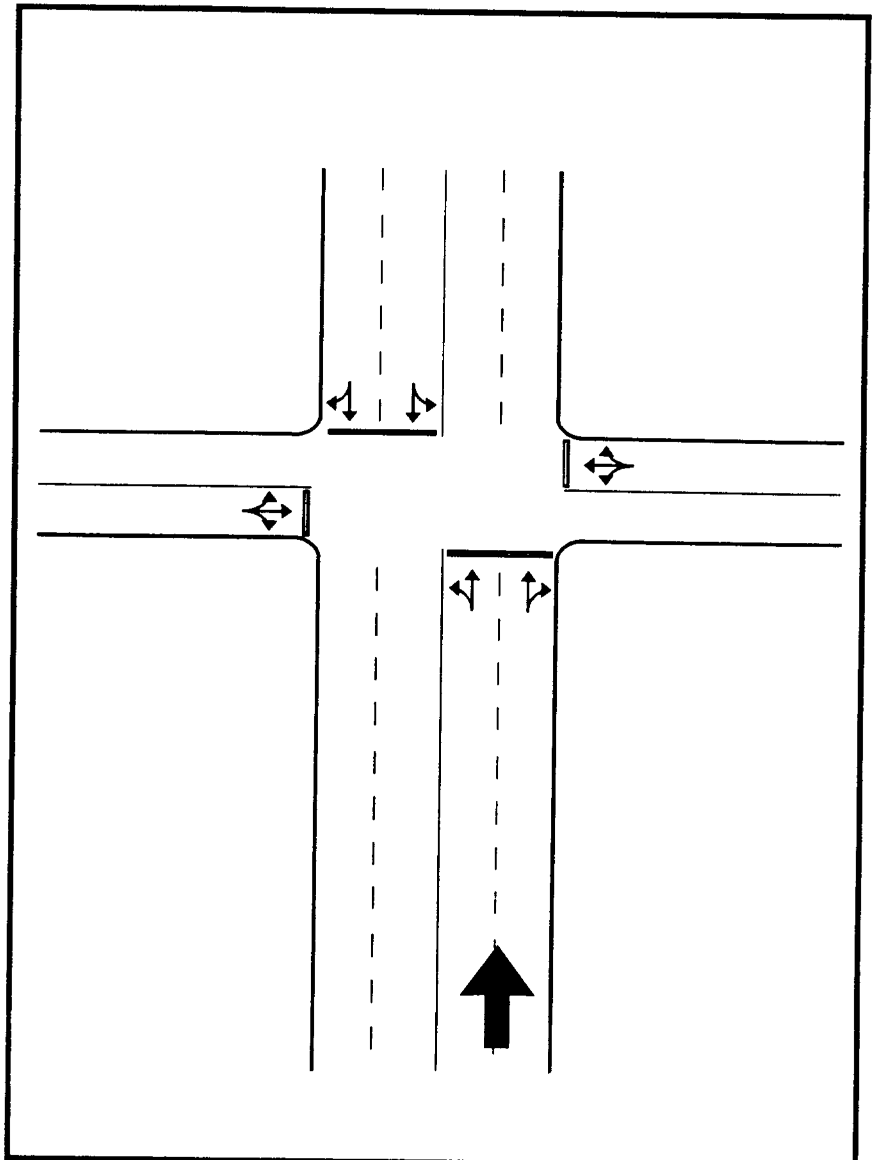

Figure 13. Intersection type 9: 4-lane by 2-lane roadway with no auxiliary lanes.

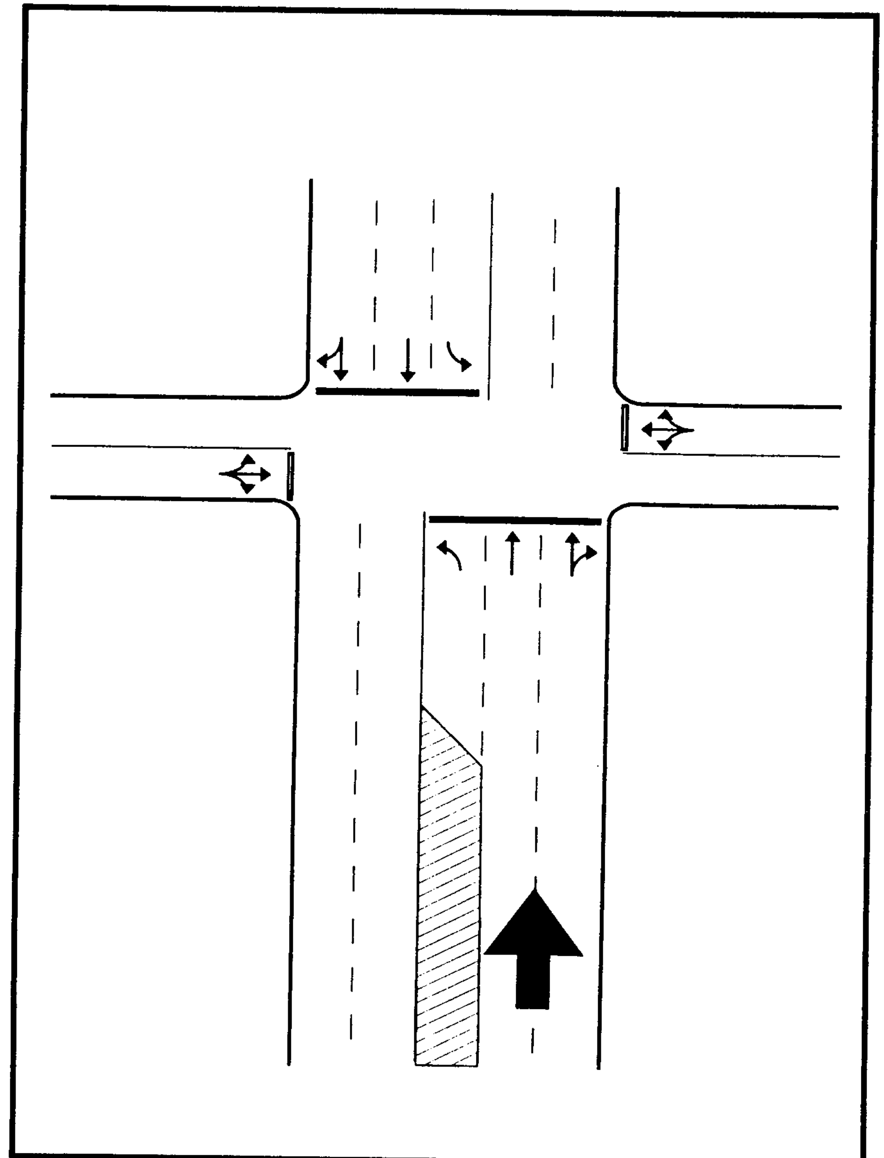

Figure 14. Intersection type 10: 4-lane roadway with opposing left-turn lanes, by 2-lane roadway.

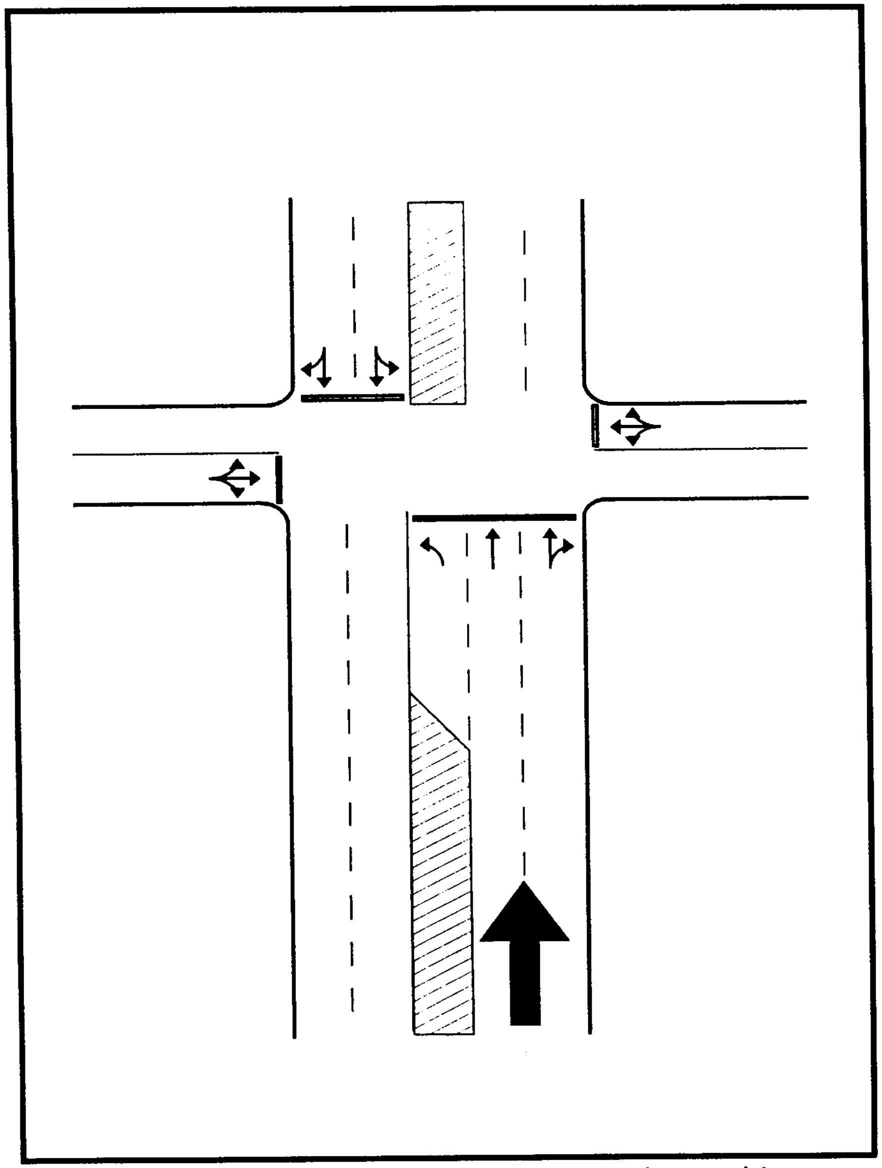

Figure 15. Intersection type 11: 4-lane roadway with non-opposing left-turn lane, by 2-lane roadway.

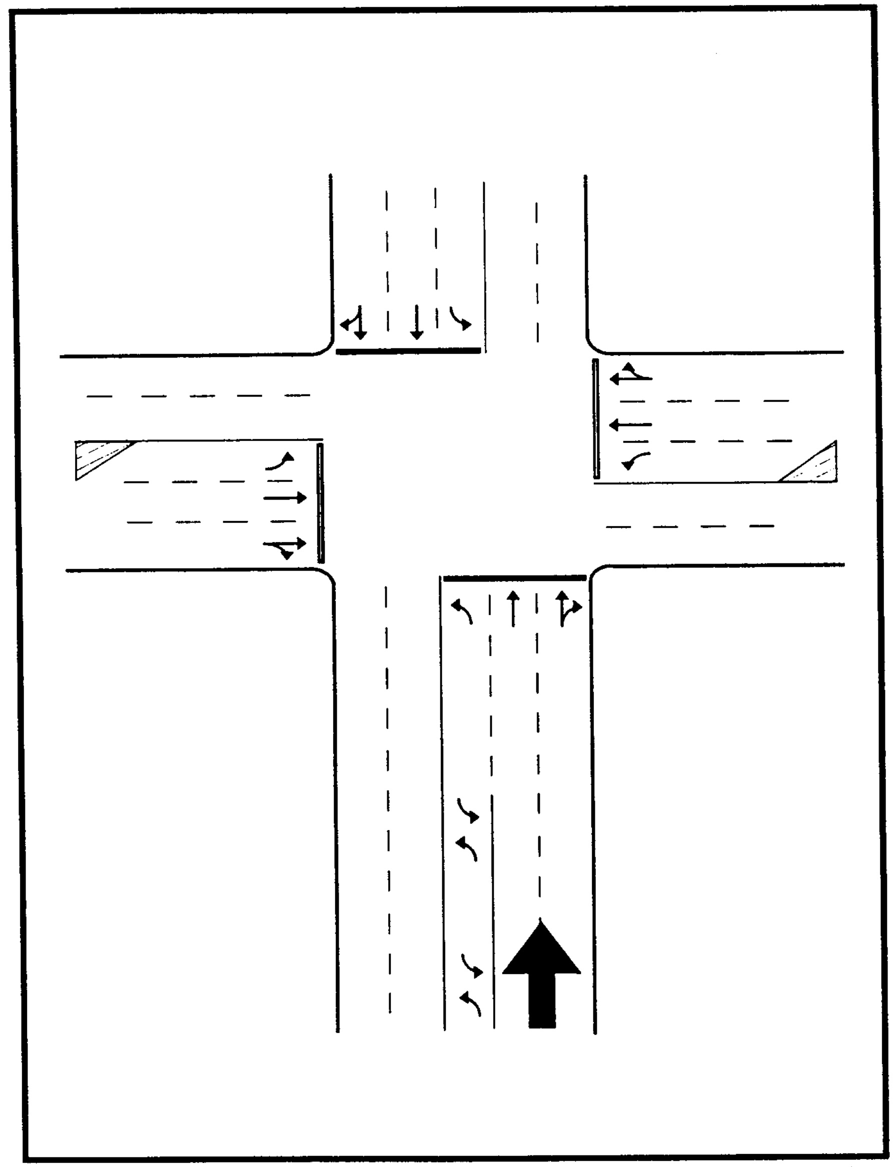

Figure 16. Intersection type 12: 4-lane roadway with opposing left-turn lanes and two-way left-turn lane approach, by 4-lane roadway with opposing left-turn lanes.

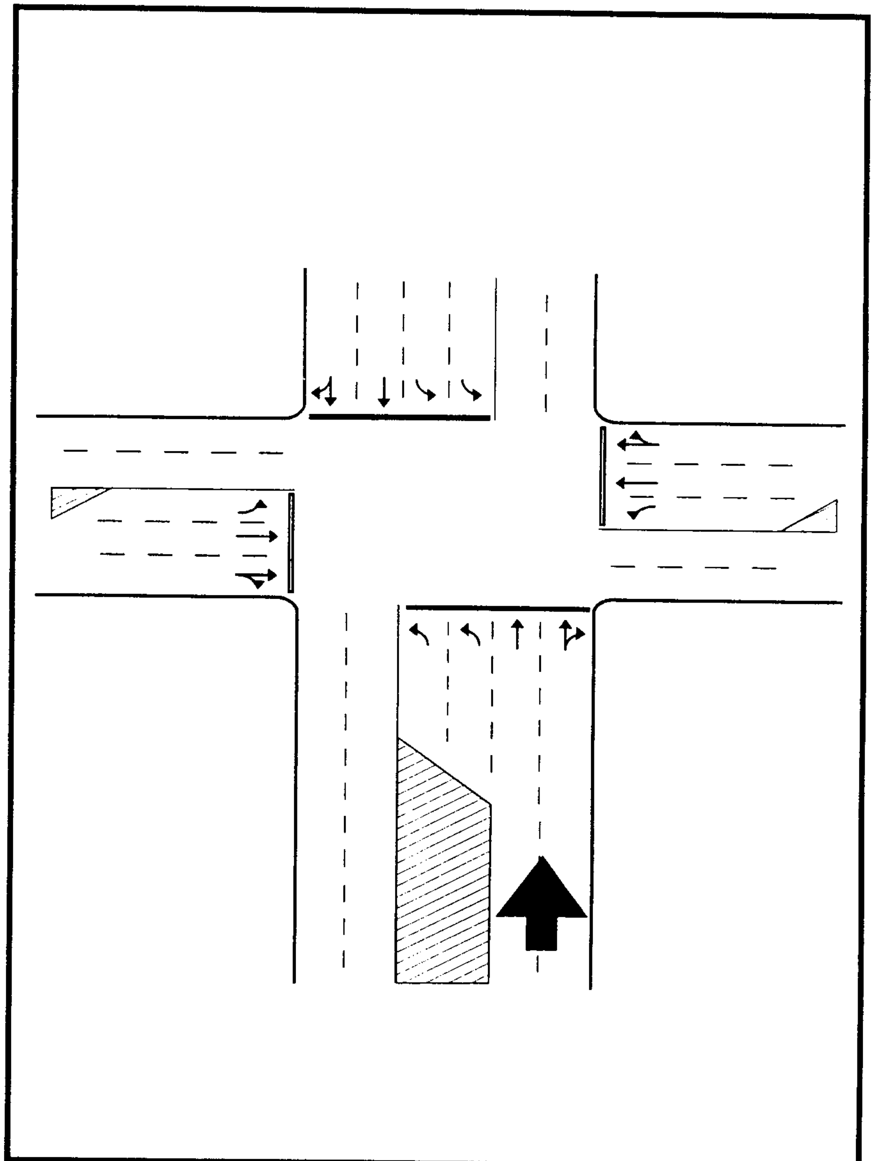

Figure 17. Intersection type 13: 4-lane roadway with opposing dual left-turn lanes, by 4-lane roadway.

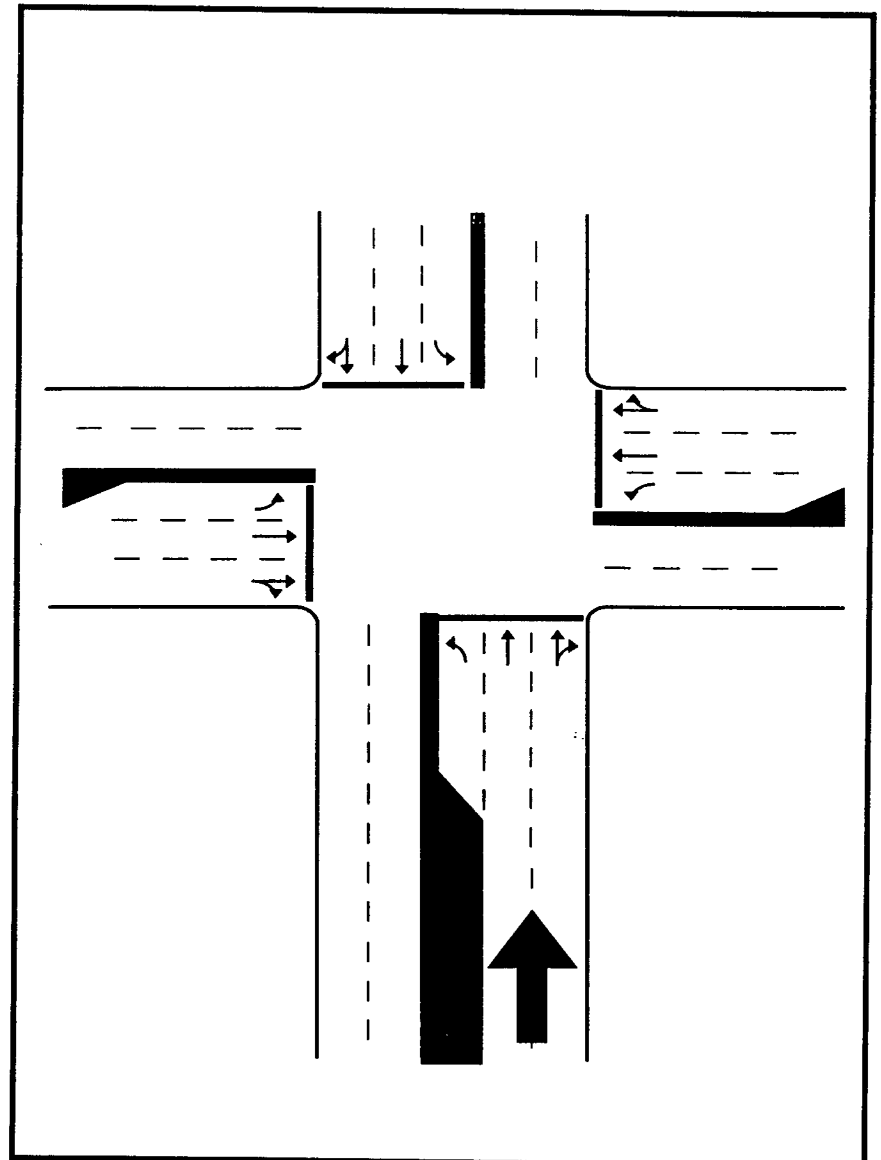

Figure 18. Intersection type 14: Divided 4-lane by 4-lane roadway with opposing left-turn lanes.

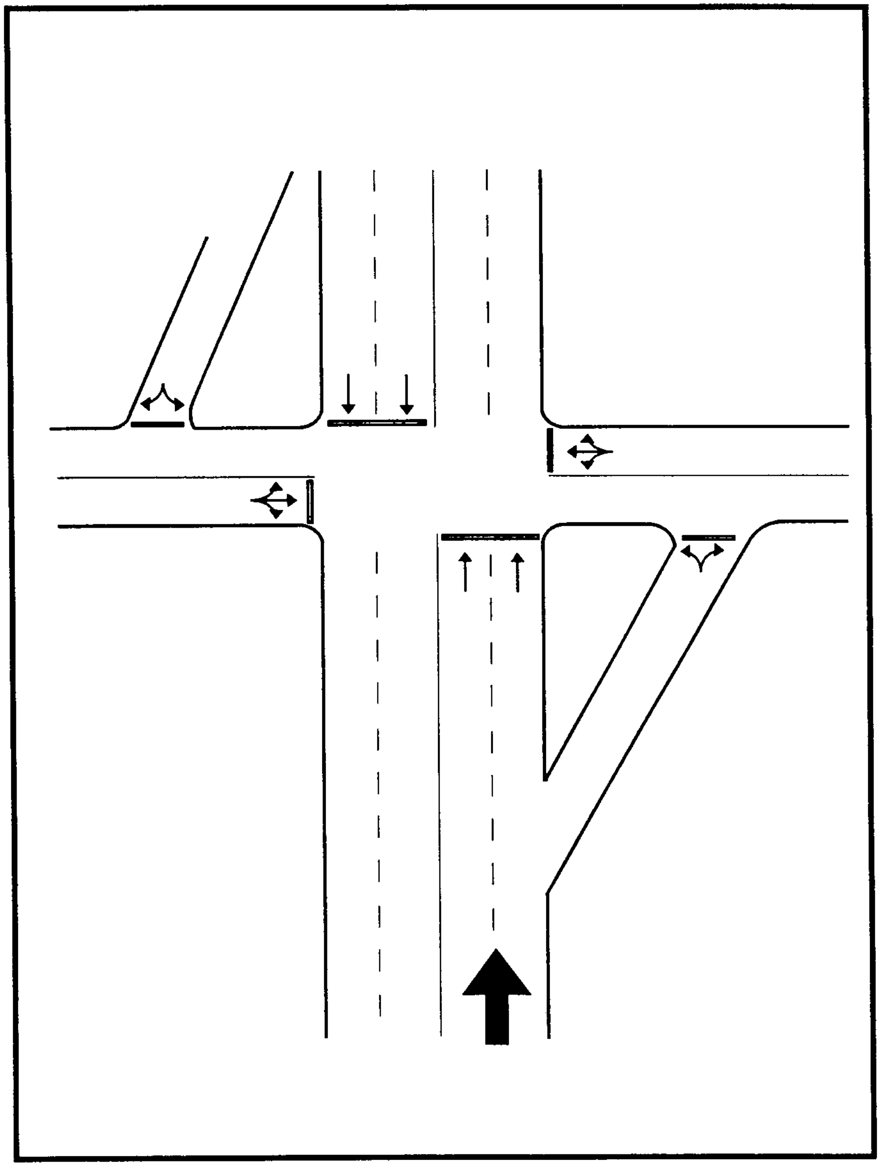

Figure 19. Intersection type 15: 4-lane roadway with jughandle-type ramp at 2-lane crossroad.

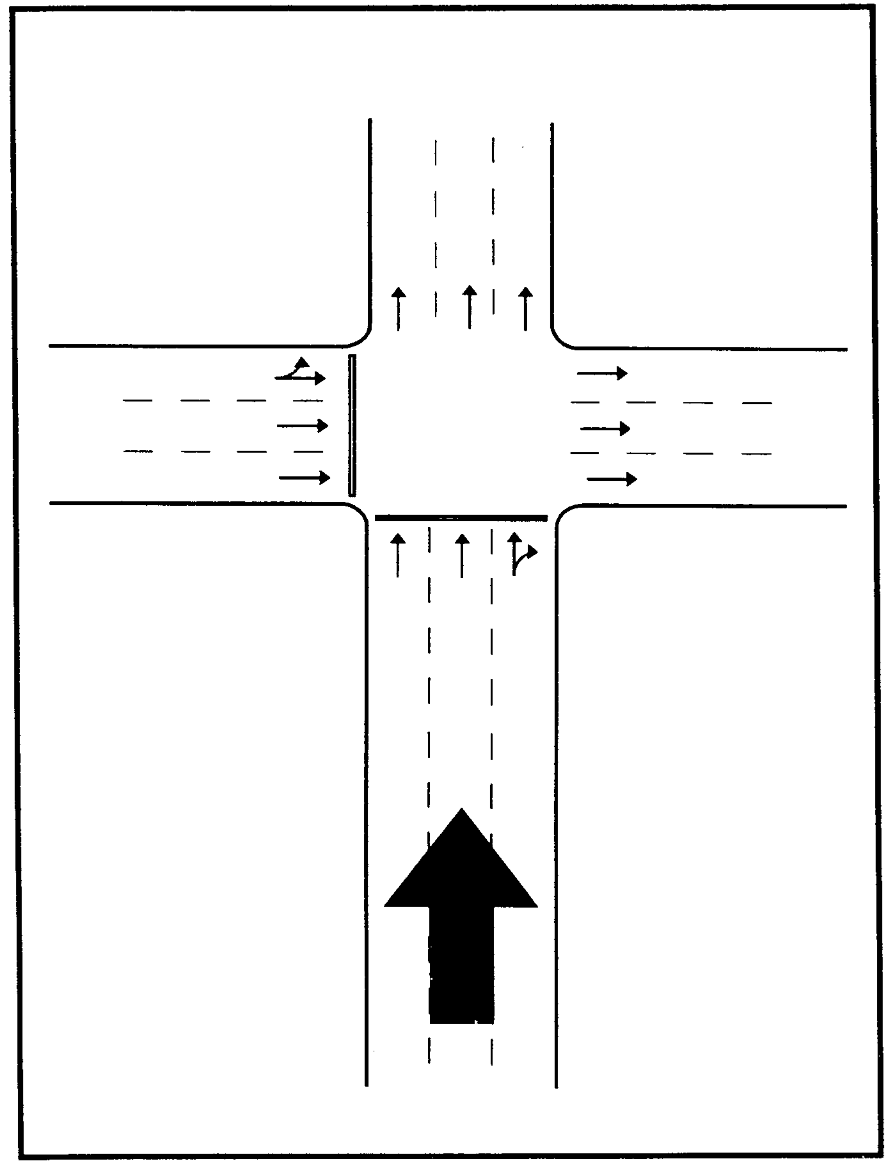

Figure 20. Intersection type 16: 3-lane one-way roadway with no auxiliary lanes, by 3-lane one-way roadway.

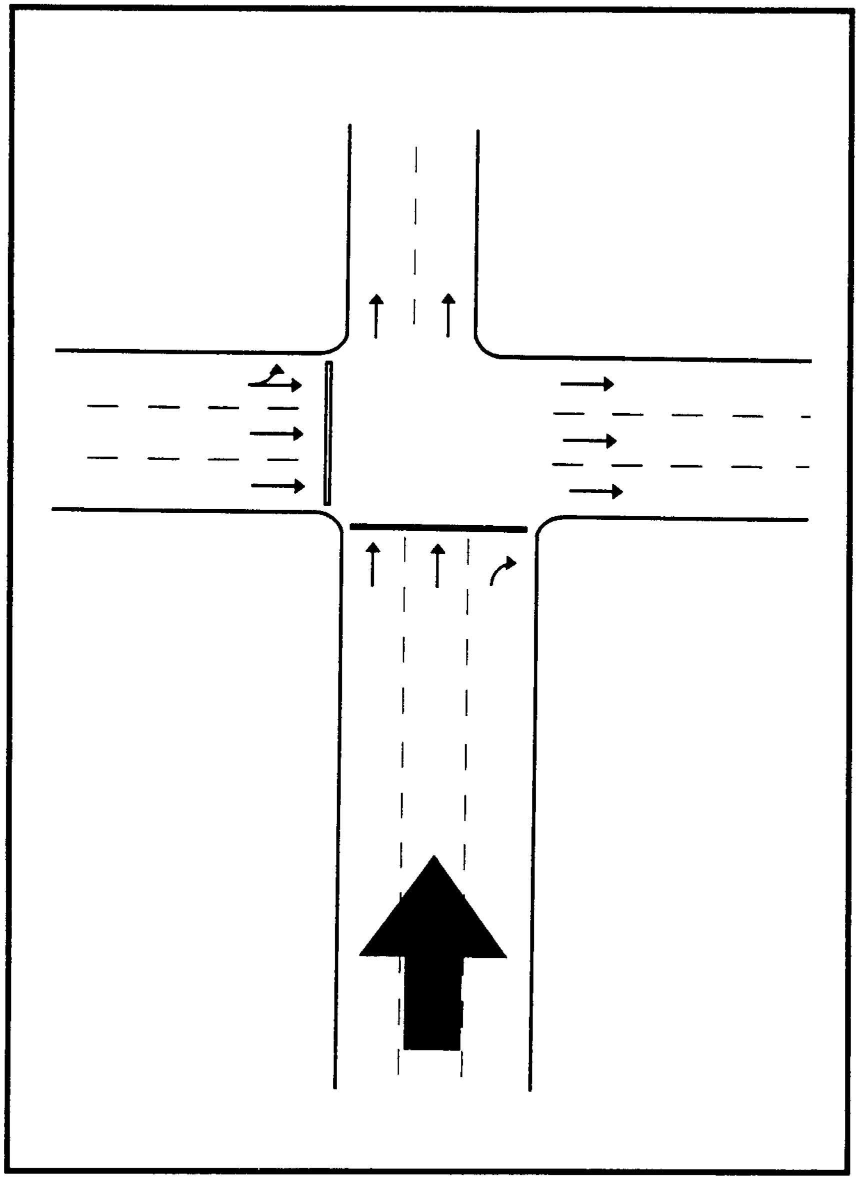

Figure 21. Intersection type 17: 3-lane one-way roadway with right-turn-only lane, by 3-lane one-way roadway.

IDENTIFICATION OF PERFORMANCE DEMANDS

A brief overview of the tasks performed at intersections serves as a useful introduction to the identification of critical demands upon older drivers in safely executing specified movements under designated traffic control (sign and signal) conditions.

As a driver approaches an intersection with the intention of traveling straight through the intersection, turning left, or turning right, he/she must first determine whether the currently traveled lane is the proper one for executing the intended maneuver. This understanding of the downstream intersection geometry is accomplished by the driver's visual search and successful detection, recognition, and comprehension of pavement markings, regulatory and/or advisory signs mounted overhead, in the median, and/or on the shoulder in advance of the intersection, and other geometric feature cues such as curb and pavement edge lines, pavement width transitions, and surface texture differences connoting shoulder or median areas.

If a lane change is required to execute a planned maneuver downstream, the driver must scan for possible conflict vehicles using a rearview or sideview mirror, and/or by direct looks over the left or right shoulder. Once detected, the speed and distance of following vehicles must be processed in a timely and accurate manner so the driver can determine when a safe gap exists to begin the lane change, and how quickly the lane change must be completed. As the driver continues to approach the intersection, diverting his/her attention as required from the ongoing activities of lane keeping (tracking) and speed adjustment to ensure a safe following distance, he/she must correctly discern the decision rule about intersection right-of-way as a function of lane position and traffic control information and may, depending upon level of route familiarity, also actively search for navigational cues to confirm correct heading or make a turn ahead.

For a left turn at a stop-sign-controlled intersection, or on an unprotected left-turn phase at a signalized intersection, for example, the driver may be required to detect oncoming traffic and make judgments about when a safe gap exists to turn left in front of opposing traffic. For right-turn situations, the driver must process speed and distance information for vehicles in the traffic stream approaching from the left. In addition to detecting potential conflict vehicles, drivers must be able to detect pedestrian crosswalk locations, and the presence of pedestrians in the crosswalks or standing on the curbside, ready to step out into traffic.

This general overview of intersection approach and negotiation tasks provides the framework for the more focused examination of task elements in the light of known age-related functional declines of older drivers which follows. This material draws upon the prior task analysis of McKnight and Adams (1970) and, from this starting point, examines all of the activities required in carrying out a particular maneuver, at a particular intersection type, controlled by a particular sign or signal condition.

It quickly became apparent in this effort that any attempt to describe intersection problems in terms of several hundred different task elements would be enormously time consuming and highly repetitive. A review of the specific problems older drivers encounter with the various combinations of intersection types, signals/signs, and maneuvers shows problems clustering primarily around signs and devices, for example responses to a green ball create rather different requirements than stop signs. Therefore, this discussion is structured hierarchically in terms of signs or signals, with maneuvers and intersection types being differentiated within sign/signal types.

Steady Green Ball

At first glance, the steady green ball would seem to be among the less demanding traffic signals to confront older drivers. Since it controls cross traffic, it would appear to burden only the left-turning driver. However, the fact that the green ball tends to facilitate the flow of traffic creates requirements for speed and timesharing that can make maneuvers under the green light more demanding than those which, although inherently more burdensome, allow the driver to proceed more slowly or to stop completely.

Through Traffic. Under simple roadway configurations, through traffic under a steady green light imposes virtually no demands for which older drivers are unprepared to cope. However, intersection problems can arise when alternative lane assignments for various maneuvers present drivers with lane choices that must be made quickly. Deficiencies in visual acuity, information processing, and simple lack of knowledge as to what various symbols mean can lead to sudden speed reductions or lane changes. The likelihood of problems increases with the complexity of the intersection in types 8 through 17. Having made an incorrect choice, and being trapped in a left-turn lane in the face of an opposing left-turn lane heightens the risk of a response that jeopardizes safety. Where sudden lane changes are required by the older driver in order to comply with lane assignments, the likelihood of the driver's detecting other vehicles in neighboring lanes is reduced by the reduced head rotation resulting from limited range of neck and upper torso motion.

Where the through lane is shared with right- or left-turning traffic, through-traveling older drivers may not anticipate or notice deceleration of vehicles ahead preparing for turns.

Left-Turns. Several problems complicate safe left turns in the phase of a steady green light.

- *Oncoming Vehicles* — The need to turn across oncoming traffic forces drivers to assess the adequacy of gaps in the oncoming traffic stream, a perceptual task for which older drivers as a group have evidenced difficulty. The closer the oncoming lane is to the lane from which it is viewed by the older driver, the more difficult it is to judge gap size. The danger of misestimation is greatest when oncoming vehicles are traveling faster than other traffic, although problems occasionally arise when they are traveling more slowly than expected (the older driver becomes impatient and initiates a left turn just as the oncoming vehicle reaches the intersection).

- *Path Search* — The fact that the green light permits pedestrians to cross the side street, where they enter the path of the left-turning vehicle, places a burden upon the driver to search the left-turning path ahead. The result is the need to share attention between oncoming vehicles in the path ahead and pedestrians in the path to the left, attention sharing being recognized as age-diminished skill. Limitations in the range of visual attention, frequently referred to as "useful field of view," further contribute to the difficulty of older drivers in detecting the presence of pedestrians or other vehicles near the driver's path.

- *Lane Keeping* — Two influences can compromise the ability of older drivers to remain within the boundaries of their assigned lanes during a left turn. One is the attention sharing just described. The other involves the ability to turn the steering wheel sharply enough, given the speed at which they are traveling, to remain within the boundaries of their lanes. Some older drivers seek to increase their turning radii by initiating the turn early and rounding off the turn. The result is either to cut across the apex of the turn, conflicting with vehicles approaching from the left or to intrude upon a far lane in completing the turn.

- *Uncertainty*—Potential conflicts with oncoming vehicles, along with the mental load created by attention sharing can lead to uncertainty and indecision resulting in sudden speed reductions and stops not anticipated by following drivers. Where opposing left-turn lanes are aligned (rather than offset or misaligned), older drivers may evidence indecision as to whether to initiate a turn short of or just beyond an oncoming left-turning vehicle. Uncertainty may lead to erratic turns and sudden stops. Multiple left-turn lanes can also lead to uncertainty leading to unexpected lane changes, while lane keeping deficiencies can lead to encroachment upon neighboring lanes.

Right Turn. A significant problem in right turns at green lights is carrying out the tight, right-turn maneuver at normal travel speed. Older drivers may seek to increase the turning radius by moving to the left before initiating the turn, often miscommunicating an intent to turn left and encouraging following drivers to pass on the right. Or, they may initiate the turn from the correct position, but swing wide into a far lane in completing the turn. Encroaching upon a far lane can lead to conflict with vehicles approaching from the right or, on multi-lane roads, oncoming drivers turning to their left at the same time. The third possibility is to cut across the apex of the turn, possibly dragging the rear wheels over the curb. Each of these shortcomings in lanekeeping can be overcome by a channelized right-turn lane.

Right-turning drivers face the same possible conflict with pedestrians as left-turning drivers and are burdened with the same attention-sharing tasks. And here again, restrictions in the visual attention allow pedestrian and vehicular traffic to go unnoticed.

Green Arrows

By regulating the direction of oncoming traffic, green arrows reduce potential conflict with oncoming vehicles, thereby also limiting attention-sharing demands. Except where separate cycles regulate pedestrian traffic, older drivers face the same potential conflicts and attention-sharing demands with pedestrians as are encountered with the green ball. The same lanekeeping problems in negotiating left and right turns are also encountered.

Steady Red Ball

This traffic control is considered only in relation to *right turns* (right-turn on red), since it is only in such maneuvers that any motion occurs at all.

Gap Selection. The requirement to yield to cross traffic burdens the right-turning driver with the need to assess the adequacy of gaps approaching from the left. The proximity of the driver to the path of the oncoming vehicle minimizes the availability of gap judgment cues, which places older persons at a particular disadvantage.

Visual Search. The fact that visual search is performed while the vehicle is stationary reduces the attention-sharing tasks that complicate turns at green lights. The fact that the driver need only contend with upstream traffic can lead to a preoccupation with search to the left and consequent failure to observe pedestrians entering the vehicle's path from the right. The attentional limitations of older drivers further decreases the likelihood of detecting pedestrians. The risk of conflict in right turns on red is elevated by the pedestrian's expectation that the red light will stabilize traffic.

Lanekeeping. While motor limitations can lead to lanekeeping problems similar to those encountered with green balls and arrows, the problems are moderated somewhat by the fact that the right turn is initiated from the stopped position. Because the turn is made more slowly, the older driver does not have as much difficulty with the short radius. And, because vehicular and pedestrian traffic can be observed before the turn is initiated, the attention-sharing demands are not as great as when turning on green lights.

Uncertainty. The visual search and gap acceptance problems described, combined with the information processing deficiencies of older drivers, are likely to lead to uncertainty, manifesting itself in aborted maneuvers which may go unnoticed by following drivers who have focused their attention upstream.

Flashing Red Light

Because the flashing red light allows the older driver to cross traffic streams from either direction, the potential risk is relatively high.

Through Traffic. Drivers proceeding straight through the flashing red ball must yield to vehicles approaching from each direction. Gap acceptance is a potential problem for older drivers. Gaps from the left will be more difficult to judge than gaps from the right due to the angle of approach. The fact that intersections must be approached at a slow speed in preparation for a stop minimizes the effects of uncertainty as to lane assignments, while the need to come to a full stop before entering the intersection minimizes attention-sharing demands. Additionally, the fact that cross traffic is approaching under a caution light offers somewhat greater protection for the older driver than would be available at a stop-sign controlled intersection.

Left Turns. Problems encountered in left turns on a flashing red light are similar to those described earlier in connection with green lights, although there are a few differences.

- *Gap Selection* — Problems in gap selection are essentially the same as those encountered in proceeding through the intersection. When entering multi-lane roads (e.g., intersection types 13 - 14), drivers need only a gap in the near lane since they will not be crossing the far lane; however, the requirement to monitor traffic approaching from the right for sudden lane changes further complicates the attention-sharing task.

- *Visual Search* — While drivers must search through the turn for pedestrians or other potential sources of conflict, attention-sharing demands are minimized by the ability to carry out search patterns before the turn is initiated, while the vehicle is stopped (unlike a left turn on a green light).

- *Lane Keeping* — While the lanekeeping tasks are the same as those encountered at the same intersections on a green ball, the fact that turns are initiated from a stopped position means they are performed at slower speeds where any motor limitations are less likely to result in lane excursions.

- *Lane Selection* — While older drivers are no more likely than anyone else to select the wrong lane in which to initiate a left turn, some may be unfamiliar with shared left-turn lanes (intersection type 8, 12) with the result that they enter the left lane well in advance of the turn, encountering an oncoming driver who has entered the same lane intending to turn left (e.g. into an alley or driveway).

- *Right Exits* — Where left turns would be extremely disruptive of traffic, the intersection configuration may call upon left-turning drivers to exit the road being traveled via a ramp from the right lane and turn left onto the cross street at a point where it will not interfere with oncoming traffic, and then traverse the intersection with cross traffic (e.g., type 15). Not specifically seeking route guidance in approaching the intersection, the older driver may fail to notice instructions to exit to the right and thus may arrive at the intersection expecting to turn left from the left lane. Further, he/she may fail to notice the left-turn prohibition at the intersection and stop to await a left turn, interfering with the progress of following drivers.

Right Turn. Problems encountered by older drivers in right turns would be similar to those described in connection with a steady red ball (i.e., right turn on red [RTOR]). However, here the problem of pedestrians crossing from the right while the driver's attention is directed to the left is tempered by the recognition by most pedestrians that the flashing red light is not expected to stabilize traffic to the same degree as a red ball.

Flashing Yellow Ball

Maneuvering tasks imposed upon drivers by a flashing yellow ball are similar to those for a solid green ball, except that the reduced control over cross traffic that a flashing red light offers relative to a red ball demands greater caution in the form of reduced speed and increased lateral search, which are areas where older persons are not particularly deficient. The one shortcoming of older drivers that may place them in jeopardy is their restricted range of motion, which could reduce their chances of detecting potential conflicts.

The flashing yellow ball may actually enhance the safety of older drivers by allowing them to reduce speed upon an approach to an intersection without increasing their vulnerability to following traffic. Being able to initiate right or left turns at slower speeds reduces motor demands, improves lanekeeping and facilitates attention-sharing by giving more time to identify and respond to lane assignments.

Steady Yellow Ball

A steady yellow ball represents a transition between a steady green ball and a steady red ball and may be responded to as either one or the other. Therefore, it relates to the previous discussion, primarily in the uncertainty involved in deciding which way any individual driver will respond. Older drivers, with their characteristic caution, seem more likely to initiate a stop when close to or actually in the intersection (when they could actually make it through) than would their younger counterparts, with the result that they decelerate when the following driver does not expect it (and may in fact be accelerating in order to beat the light).

Yellow Arrow

A yellow arrow has the same significance for drivers approaching a protected turn as a yellow ball has for intersections in general — the key ingredient is primarily uncertainty. With the yellow ball, the uncertainty largely concerns whether or not the driver can clear the intersection before the light turns red. However, in the case of the yellow arrow, uncertainty also includes what form the next signal will take. Under the next signal, the driver may be prohibited from turning in the direction indicated (e.g., from yellow arrow to red arrow, or to a green arrow in another direction), or permitted to turn, but without protection (from yellow arrow to green ball). As a result, drivers may stop when they could have continued, or expect to be able to continue when it turns out that they cannot. Such confusion is only compounded by the effects of age.

Two-Way Stop

Stop signs controlling traffic from two directions are similar to flashing red lights, except that cross traffic is not operating under a yellow caution light. As noted previously, cross traffic may be proceeding somewhat more rapidly and drivers may be less prepared to accommodate to errors made by crossing or turning drivers. Otherwise, there is little difference in the tasks of gap selection, lanekeeping, and so on.

Four-Way Stop

The four-way stop is probably the most forgiving to the deficiencies of older drivers in that maneuvers are executed at slow speeds. While the same is true of other traffic controls requiring the vehicle to stop, the driver is not presented with the gap selection task which arises with red lights and stop signs. Even when confused about priorities (who goes first), the result is not likely to be a serious crash. The problems encountered at 4-way stops involve primarily the lane keeping tasks created by turning maneuvers themselves which, if anything, are benefitted by the necessity to perform them at low speed.

Yield Sign

A "yield" sign facilitates traffic flow by preventing unnecessary stops and allowing drivers to enter the traffic flow with minimum disruption of through traffic. Most yield signs are posted where right-turning drivers can approach the cross street at an oblique angle. Such configurations benefit older drivers in carrying out the turning maneuver by avoiding the tight radii that characterize right-angle turns. However, in several respects, intersections regulated by yield signs place greater demands upon drivers than those employing other controls.

Gap Selection. The angle of approach to the street or highway being entered ranges from the near perpendicular to the near parallel. The closer is the angle to the parallel, the further must the driver's head be turned to detect and to judge the speed and distance of vehicles on the road to be entered. Many older drivers are unable to turn their heads far enough to get a good look at approaching traffic, while the need to share attention with the road ahead necessarily limits the lane exposure to one or two seconds. Some drivers are reduced to attempting to judge distance and gaps by means of the outside mirror. The inability to judge gaps in this manner often results in the driver reaching the end of the access lane without having identified an appropriate gap. The driver in this situation comes to a complete stop and then must enter the cross street by accelerating from a stopped position.

Lanekeeping. The need to share attention between two widely separated points results in eyes being off the intended path for lengthy periods. The diversion of attention, along with movement of the upper torso, hampers the older driver's ability to maintain directional control.

Vehicle Speed. It is not unusual for older drivers entering a road or highway from an access lane to proceed to the end of the access lane and come to a stop to await a gap, even when the access lane is of ample length. Some drivers have simply reached the end of the access lane before a gap has materialized. Other older drivers, however, simply do not know the purpose for and use of an access lane.

Uncertainty. The difficulty in judging gaps may lead to aborted attempts to enter the highway, leaving the older driver vulnerable to following drivers who direct their attentions upstream and fail to notice that a vehicle has stopped in front of them.

ASSIGNING RELATIVE ERROR AND CRASH LIKELIHOOD RATINGS

After generating a list of problems that older drivers are likely to have at intersections for each possible combination of traffic control device (e.g., solid green lights, flashing red lights, yellow arrows, stop signs, etc.) and the driver's intended vehicle movement/maneuver (i.e., proceed straight, turn left, turn right), the task analysis developed "criticality" ratings reflecting the judged relative error and crash likelihoods for every potential problem.

The likelihood that older drivers would make errors, or be involved in crashes, in each instance was assessed by two members of the research team with experience at rating driving behaviors for their criticality to safe driving. Ratings were made using a five-point scale, assumed for this analysis to have interval properties. Values were assigned according to the raters' opinions of the independent probabilities that an older driver would make a behavioral error, and that he/she would be involved in a crash if such an error should occur, in each situation.

Table 9 shows the crash probabilities that correspond to each rating. As indicated in this table, probability values are skewed toward the lower end of the scale, acknowledging the infrequency (in an *absolute* sense) with which crashes result for any of the errors and situations considered in this analysis.

Table 9. Ratings assigned to error likelihood and crash probability in the prioritization of older drivers' problems at intersections.

Probability	Rating
<01%	1
01-05%	2
06-25%	3
26-50%	4
>50%	5

As an example, if it was believed that an older driver faced with a solid yellow light would stop unnecessarily 10 percent of the time, a value of 3 would be assigned to that error likelihood rating. If it was believed that stopping unnecessarily for a yellow light would result in a crash 10 percent of the time this behavior occurred, a value of 3 would be assigned to that crash likelihood rating.

When initial ratings were compared, it was found that most of the items were rated the same or within one point by the two raters. After discussion between the raters and agreement on any items that differed by more than one point, the correlation between the two ratings of error likelihood was $r = 0.63$, $p < 0.001$, and the correlation for crash likelihood was $r = 0.73$, $p < 0.001$. The ratings that differed by one point were discussed further and a rating was agreed upon.

Considerations for Rating Error Probabilities

In rating the probabilities that older drivers would make errors, the raters considered the following:

- Known tendencies of older drivers to make certain types of errors.

- The effect of intersection complexity on older drivers' cognitive workload.

- The speeds that would normally be associated with the intersections and maneuvers involved, and the effect of those speeds on cognitive workload.

- The extent to which increased traffic density might increase the visual/cognitive workload and/or occlude sight lines.

- The extent to which the likelihood and/or severity of a potential collision might affect the older driver's tendency to make an error, e.g., are older drivers less likely to infringe upon an oncoming lane than an adjacent lane that travels in the same direction, knowing that a collision with an oncoming vehicle is likely to be more severe.

In assigning ratings it was assumed that the driver was faced with this maneuver/traffic control device type. For example, the probability of stopping unnecessarily for a yellow arrow at an intersection did *not* include the probability of encountering an intersection with yellow arrow, making a turn at that intersection or happening to arrive at the intersection just as the yellow arrow was lighting.

Considerations for Rating Crash Probabilities

In rating the probabilities that older drivers' errors may result in crashes, the raters considered the following:

- Traffic densities and speeds and their contribution to the likelihood of conflict with other drivers.

- The extent to which the error is likely to result in a deviation in speed or path of the older driver sufficient to cause conflict with another driver.

- The ability of other drivers to compensate for the older driver's error (this is in turn affected by perceptual and cognitive workloads that vary as a function of intersection complexities, speeds, traffic densities, etc.).

- Times to collision, which vary as a function of relative speeds, directions and sight lines of the drivers involved.

- The likelihood of other drivers making maneuvers that would contribute to a crash (for example, the likelihood that an older driver will be involved in a crash while passing through a flashing yellow light is affected partly by the likelihood of another driver violating the older driver's right-of-way by pulling out from a flashing red light).

In all cases it was assumed that the older driver had made an error, so the likelihood of a crash is rated independently of the likelihood of an error.

Consideration of Intersection Types

Intersection types were omitted for certain traffic control devices when it was assumed that the combinations would be either unlikely (e.g., stop signs at extremely complex intersection), or impossible (e.g., left-turn arrows at an intersection with a one-way street running from left to right).

In some cases, design characteristics of intersections affected error or crash likelihoods so that two groups of intersection types that differed on the basis of some design characteristic were rated separately. For example, it was assumed that older drivers would be less likely to swing into an adjacent lane to facilitate a turn when the adjacent is an oncoming lane. Hence, the likelihood of making that error is different depending on whether the intersection design is such that a swing into an adjacent lane would take the driver into an oncoming lane. Table 10 below explains cases in which intersections were divided into separate groups for the rating of error and crash likelihoods.

Table 10. Reasons for separating intersection types and applicable older driver problems. [NOTE: Problem identification numbers reference entries in Table 11].

Reason for Separating Intersection Types	Applicable Older Driver Problems
Increased channelization should reduce the likelihood of errors.	1.1.1, 1.1.3, 1.1.4, 5.1.2, 5.1.3, 5.1.4
Lines of vehicles on the oncoming road that are stopped to turn left may block the view of oncoming vehicles. This intersection geometry is likely to increase the probability of both errors and crashes since neither the older driver, nor the oncoming driver can see each other.	1.2.1
Increased error likelihood as complexity of intersection increases.	1.2.1, 1.2.2, 1.2.5, 1.3.4, 5.2.1, 5.2.2, 5.2.5
Drivers may be less likely to swing into oncoming lanes than lanes traveling the same direction. Reduced time to collision may increase crash likelihood.	1.3.1, 1.3.2, 2.2.2, 3.1.3, 5.3.1
Error likelihood may be reduced when turning across two oncoming lanes (as opposed to one) due to decreased turn angle.	2.1.2, 5.2.4
Error likelihood increases when cars in adjacent lanes can block the view of the cross street ahead.	5.1.1
The need to look back at a sharper angle increases the likelihood of errors.	9.1, 9.3, 9.4

Total Criticality

A Total Criticality rating was created by multiplying the error likelihood by the crash likelihood.

The relative error and crash likelihood ratings from this task analysis, and the resultant Total Criticality value for each identified older driver intersection negotiation problem, are presented in Table 11. As indicated in this table, older driver problems (level X.X.X) are differentiated with respect to combinations of traffic control (level X) by intersection maneuver (level X.X) for each applicable intersection type (see Figures 5 through 21).

Table 11. Criticality ratings of older driver problems identified in task analysis.

OLDER DRIVER PROBLEM	Likelihood of Error	Likelihood of Crash	Total	Intersection Types (see Figures 5-21)
1. Steady Green Ball				
1.1 Through Traffic				
1.1.1 Entering wrong lane for through traffic due to inability to perceive lane assignments quickly	2 3	1 1	2 3	5, 7 8, 12, 17
1.1.2 Slowing suddenly due to inability to perceive lane assignments or understand destination signs quickly	3	2	6	All except 1, 2, 3
1.1.3 Entering the path of an overtaking vehicle due to the need to change lanes quickly and the lack of proper visual search	1 2	3 3	3 6	5, 7 8, 12, 17
1.1.4 Entering the path of an overtaking vehicle slowly or from a stop after being trapped in the wrong lane	1 2	2 2	2 4	5, 7 8, 12, 17
1.1.5 Overtaking a lead vehicle slowing for a turn due to failure to detect turn signal or closing rate	2	2	4	All except 1, 2, 3, 17
1.2 Left Turn				
1.2.1 Turning into the path of an oncoming vehicle due to underestimation of the vehicle's speed, or overestimation followed by impatience	1 2	2 3	2 6	4, 5, 6, 7, 8 9, 10, 11, 12, 13, 14

Table 11 (Continued). Criticality ratings of older driver problems identified in task analysis.

OLDER DRIVER PROBLEM	Likelihood of Error	Likelihood of Crash	Total	Intersection Types (see Figures 5-21)
1.2.2 Turning into the path of an oncoming vehicle or into pedestrians crossing path to the left, due to limitations in parafoveal vision and ability to share attention	2 3	2 3	4 9	2, 3, 4, 5, 6, 7, 8 9, 10, 11, 12, 13, 14, 15
1.2.3 Swinging wide and encroaching upon a far lane due to attention-sharing and/or difficulty in turning steering wheel quickly enough for speed of travel	3	1	3	12, 13, 14
1.2.4 Beginning turn too early and cutting across apex due to attention sharing or difficulty turning steering wheel quickly enough for speed of travel	2 1	1 1	2 1	1, 2, 3, 4, 5, 6, 7, 8, 15 9, 10, 11, 12, 13
1.2.5 Slowing or stopping suddenly due to confusion as to direction, lane choice, or path with respect to oncoming left-turning vehicles (i.e. whether turn before or beyond the vehicle)	2 3	2 2	4 6	1, 2, 3, 4, 5, 6, 7, 8 9, 10, 11, 12, 13, 14
1.2.6 Conflict with oncoming left-turning vehicle by premature entry to shared left turn lane, due to unfamiliarity with pavement marking	3	1	3	8, 12

Table 11 (Continued). Criticality ratings of older driver problems identified in task analysis.

OLDER DRIVER PROBLEM	Likelihood of Error	Likelihood of Crash	Total	Intersection Types (see Figures 5-21)
1.2.7 Failing to notice where left turn is initiated from a right lane (via ramp to cross-street), changing lanes to the right at the last moment	3	2	6	15
1.2.8 Failing to notice where left turn is initiated from a right lane (via ramp to cross-street), remaining in the left lane with the need to slow and make left turn unexpectedly	2	1	2	15
1.3 Right Turn				
1.3.1 Moving left before initiating turn in order to increase turn radius and thus compensate for difficulty turning steering wheel quickly enough for speed of travel	2 3	1 2	2 6	1, 2, 4 5, 7, 8, 9, 10 ,11, 12, 13, 14, 16, 17
1.3.2 Swinging wide and encroaching upon a far lane due to difficulty in turning steering wheel quickly enough for speed of travel	1 3	2 1	2 3	1,2,3,4,5,7,8,9,10,11,15 12,13,14,16,17
1.3.3 Dragging right rear wheel across curb, sidewalk etc. by initiating turn early, due to difficulty in turning steering wheel quickly enough for speed of travel	2	1	2	All except 6

Table 11 (Continued). Criticality ratings of older driver problems identified in task analysis.

OLDER DRIVER PROBLEM	Likelihood of Error	Likelihood of Crash	Total	Intersection Types (see Figures 5-21)
1.3.4 Conflict with pedestrians crossing street to the right, due to attention sharing and visual limitations	1 2	1 1	1 2	1,2,3,4,5,6,7,8,9,10,11 12,13,14,15,16,17
2. Green Arrows				
2.1 Left Turns				
2.1.1 Swinging wide and encroaching upon a far lane due to attention-sharing and/or difficulty in turning steering wheel quickly enough for speed of travel	3	1	3	12, 13, 14
2.1.2 Beginning turn too early and cutting across apex due to attention sharing or difficulty turning steering wheel quickly enough for speed of travel	2 1	1 1	2 1	5, 6, 7, 8 9, 10, 11, 12, 13
2.1.3 Slowing or stopping suddenly due to confusion as to direction, lane choice, or path with respect to oncoming left-turning vehicles (i.e. whether turn before or beyond the vehicle)	3	2	6	All

Table 11 (Continued). Criticality ratings of older driver problems identified in task analysis.

OLDER DRIVER PROBLEM	Likelihood of Error	Likelihood of Crash	Total	Intersection Types (see Figures 5-21)
2.1.4 Conflict with oncoming left-turning vehicle by premature entry to shared left turn lane, due to unfamiliarity with pavement marking	3	1	3	8, 12
2.2 Right Turns				
2.2.1 Moving left before initiating turn in order to increase turn radius and thus compensate for difficulty turning steering wheel quickly enough for speed of travel	3	2	6	5, 7, 8, 9, 10, 11, 12, 13, 14, 17
2.2.2 Swinging wide and encroaching upon a far lane due to difficulty in turning steering wheel quickly enough for speed of travel	1 3	2 1	2 3	5, 7, 8, 9, 10, 11, 15 12, 13, 14, 16, 17
2.2.3 Dragging right rear wheel across curb, sidewalk etc. by initiating turn early, due to difficulty in turning steering wheel quickly enough for speed of travel	2	1	2	All except 1, 2, 3, 4, 6, 15, 16

Table 11 (Continued). Criticality ratings of older driver problems identified in task analysis.

OLDER DRIVER PROBLEM	Likelihood of Error	Likelihood of Crash	Total	Intersection Types (see Figures 5-21)
3. Steady Red Ball				
3.1 Right Turn (on Red)				
3.1.1 Entering path of vehicle from left due to attention-sharing and difficulty in gap estimation, given the small approach angle (almost straight on)	2	3	6	All except 6
3.1.2 Conflict with pedestrians crossing from the right (not expecting vehicle to move) due to limitations in attention-sharing (with upstream traffic) and parafoveal vision	3	2	6	All except 6
3.1.3 Swinging wide and encroaching upon a far lane due to effort involved in turning steering wheel and limitations in attention-sharing	1 3	2 2	2 6	1,2,3,4,5,7,8,9,10,11,15 12,13,14,16,17

Table 11 (Continued). Criticality ratings of older driver problems identified in task analysis.

OLDER DRIVER PROBLEM	Likelihood of Error	Likelihood of Crash	Total	Intersection Types (see Figures 5-21)
3.1.4 Dragging right rear wheel across curb etc. by initiating turn early to reduce effort involved in turning steering wheel and due to limitations in attention-sharing	2	1	2	All except 6
3.1.5 Creating conflict with following vehicles by aborting turn due to 3.1.1 or 3.1.2	3	2	6	All
4. Stop Sign and Flashing Red Light				
4.1 Through Traffic				
4.1.1 Entering path of vehicle from left (facing flashing yellow) due to difficulty in gap estimation, given the small approach angle	3	3	9	4, 5, 6, 7, 8
4.1.2 Entering path of vehicle from right (on flashing yellow) due to difficulty in gap estimation	2	2	4	4, 5, 6, 7, 8
4.2 Left Turns				
4.2.1 Beginning turn too early and cutting across apex due to effort required in turning steering wheel	2	1	2	1, 2, 3, 4, 5, 6, 7, 8

Table 11 (Continued). Criticality ratings of older driver problems identified in task analysis.

OLDER DRIVER PROBLEM	Likelihood of Error	Likelihood of Crash	Total	Intersection Types (see Figures 5-21)
4.2.2 Failing to notice where left turn is initiated from a right lane (via ramp to cross-street), changing lanes to the right at the last moment	2	2	4	15
4.2.3 Failing to notice where left turn is initiated from a right lane (via ramp to cross-street), remaining in the left lane with the need to make left turn unexpectedly	2	1	2	15
4.3 Right Turn				
4.3.1 Entering path of vehicle from left due to difficulty in gap estimation, given the small approach angle (almost straight on)	2 3	3 3	6 9	1, 2, 4, 5, 7, 8 3
4.3.2 Conflict with pedestrians crossing from the right due to limitations in attention-sharing (with upstream traffic) and parafoveal vision	3	2	6	1, 2, 3, 4, 5, 7, 8
4.3.3 Swinging wide and encroaching upon a far lane due to effort involved in turning steering wheel	2	2	4	1, 2, 3, 4, 5, 7, 8

Table 11 (Continued). Criticality ratings of older driver problems identified in task analysis.

OLDER DRIVER PROBLEM	Likelihood of Error	Likelihood of Crash	Total	Intersection Types (see Figures 5-21)
4.3.4 Dragging right rear wheel across curb etc. by initiating turn early to reduce effort involved in turning steering wheel	2	1	2	1, 2, 3, 4, 5, 7, 8
5. Flashing Yellow Ball				
5.1 Through Traffic				
5.1.1 Failure to detect possible vehicle on cross street entering lane ahead, due to visual limitations	2 3	1 1	2 3	4, 5, 6, 7 10, 11, 15
5.1.2 Entering wrong lane for through traffic due to inability to perceive lane assignments quickly enough, even at reduced speed	1 2	1 1	1 2	5, 7 8, 9
5.1.3 Entering the path of an overtaking vehicle due to the need to change lanes quickly and the lack of proper visual search even at reduced speed	1 2	3 3	3 6	5, 7 8
5.1.4 Entering the path of an overtaking vehicle after being trapped in the wrong lane, even while traveling at a reduced speed	1 2	2 2	2 4	5, 7 8
5.1.5 Overtaking a lead vehicle slowing for a turn due to failure to detect turn signal or closing rate	1	2	2	4, 5, 6, 7, 8, 9, 10, 11

Table 11 (Continued). Criticality ratings of older driver problems identified in task analysis.

OLDER DRIVER PROBLEM	Likelihood of Error	Likelihood of Crash	Total	Intersection Types (see Figures 5-21)
5.2 Left Turn				
5.2.1 Turning into the path of an oncoming vehicle due to underestimation of the vehicle's speed, or overestimation followed by impatience, even at reduced speed	1 2	3 3	3 6	4, 5, 6, 7, 8 9, 10, 11, 12, 13, 14
5.2.2 Turning into the path of an oncoming vehicle or into pedestrians crossing path to the left, due to limitations in parafoveal vision and ability to share attention, even at reduced speed	2 3	2 2	4 6	4, 5, 6, 7, 8 9, 10, 11, 12, 13, 14
5.2.3 Swinging wide and encroaching upon a far lane due to attention-sharing and/or difficulty in turning steering wheel quickly enough, even at reduced speed of travel	3	1	3	12, 13, 14
5.2.4 Beginning turn too early and cutting across apex due to attention sharing or difficulty turning steering wheel quickly enough, even at reduced speed of travel	2 1	1 1	2 1	1, 2, 3, 4, 5, 6, 7, 15 9, 10, 11, 12, 13

Table 11 (Continued). Criticality ratings of older driver problems identified in task analysis.

OLDER DRIVER PROBLEM	Likelihood of Error	Likelihood of Crash	Total	Intersection Types (see Figures 5-21)
5.2.5 Slowing or stopping suddenly due to confusion as to direction, lane choice, or path with respect to oncoming left-turning vehicles (i.e. whether turn before or beyond the vehicle), even at reduced speed of travel	2 3	2 2	4 6	1, 2, 3, 4, 5, 6, 7, 8 9, 10, 11, 12, 13, 14
5.2.6 Conflict with oncoming left-turning vehicle by premature entry to shared left turn lane, due to unfamiliarity with pavement marking, even at reduced speed of travel	3	1	3	8, 12
5.3 Right Turn				
5.3.1 Moving left before initiating turn in order to increase turn radius and thus compensate for difficulty turning steering wheel quickly enough, even at reduced speed of travel	3 2	1 2	3 4	2, 5, 7, 8, 9, 10, 11 1, 4
5.3.2 Swinging wide and encroaching upon a far lane due to difficulty in turning steering wheel quickly enough, even at reduced speed of travel	3	1	3	All except 6, 12, 13, 14, 15, 16, 17

Table 11 (Continued). Criticality ratings of older driver problems identified in task analysis.

OLDER DRIVER PROBLEM	Likelihood of Error	Likelihood of Crash	Total	Intersection Types (see Figures 5-21)
5.3.3 Dragging right rear wheel across curb, sidewalk etc. by initiating turn early, due to difficulty in turning steering wheel quickly enough even at reduced speed of travel	2	1	2	All except 6, 12, 13, 14, 15, 16, 17
5.3.4 Conflict with pedestrians crossing street to the right, due to attention sharing and visual limitations, even at reduced speed of travel	1	1	1	All except 12, 13, 14, 15, 16, 17
6. Steady Yellow Ball				
6.1 Stopping unnecessarily, due to extreme caution, creating conflict with a following vehicle	3	3	9	All
7. Yellow Arrow				
7.1 Stopping unnecessarily, due to extreme caution or uncertainty as to the next signal phase (red or unprotected green), creating conflict with a following vehicle	4	2	8	All except 1, 2, 3, 4, 15, 16
8. All-Way Stop				
8.1 Confusion as to priorities may lead to failure to yield right-of-way	3	1	3	4, 5, 6

Table 11 (Continued). Criticality ratings of older driver problems identified in task analysis.

OLDER DRIVER PROBLEM	Likelihood of Error	Likelihood of Crash	Total	Intersection Types (see Figures 5-21)
9. Yield Sign				
9.1 Entering path of vehicle on main street due to difficulty in turning head, deficiencies in attention-sharing, and misestimation of speed and distance	3 4	2 3	6 12	3 6
9.2 Coming to a stop and entering the main street at a speed that leads to conflict with overtaking vehicles, due to difficulty in attention-sharing or failure to recognize acceptable gaps before reaching the end of the access lane.	3	2	6	3, 6
9.3 Failing to remain in lane due to deficiencies in attention sharing	1 3	1 1	1 3	3 6
9.4 Creating conflict with following vehicle by aborting attempt to enter main street, due to misestimation of gaps	2 3	2 4	4 12	3 6

CONCLUSIONS AND PROBLEM PRIORITIZATION

The most problematic maneuvers and their associated vehicle control behaviors, at specific sites under specific operating conditions, may be prioritized as follows in terms of the Total Criticality values derived in this task analysis.

The highest Total Criticality value of 12 was associated with intersection type 6, which is a 2-lane by 2-lane intersection, with a channelized right-turn lane and an acceleration lane. The problems older drivers are likely to experience at this type of intersection result from a combination of factors which combine to create a high likelihood of crash involvement. First, a driver turning right is controlled by a yield sign. The literature is filled with evidence that older drivers are involved in crashes because they are likely to fail to yield the right-of-way. Second, this (skewed) geometry requires a driver to maintain lane position while turning, and at the same time, look to the left to judge the speed and distance of approaching vehicles to locate a proper gap to merge into. Lane keeping poses a problem for many older drivers, which is exacerbated when the driver must maintain lane position while in a curve. Third, it is well documented that older drivers have difficulty judging the speed and distance of approaching vehicles in making gap acceptance judgments; demands upon this ability are increased because the driver is also moving, and must share attention between maintaining his/her path and integrating speed and distance information. And finally, if the approaching traffic is dense and the driver is unable to locate a gap during the approach, the driver may find him/herself at the end of the channelized lane, looking over his/her shoulder to watch for an appropriate gap. This motion is difficult for older drivers who have reduced neck and body flexibility, often coupled with arthritis. The result is that the older driver may make one of two errors which have a 25 to 50 percent probability of occurrence and the same probability of leading to a crash, once the error occurs. The driver may enter the path of a vehicle approaching on the main street, due to the older driver's difficulty turning his/her head, difficulty in attention sharing, and or difficulty in estimating the speed and distance of the approaching vehicle. Or, the driver may decide to abort his/her attempt to enter the main roadway due to misestimation of gaps, and thus create conflict with a following driver who expects the older driver to merge into traffic by using the acceleration lane.

The problems receiving the second highest Total Criticality value (9), were shared by multiple intersection types: intersection types 9 through 15 were associated with a likelihood of problem occurrence of 6 to 25 percent, also leading to a crash 6 to 25 percent of the time. In each case, the problem situation is defined by an older driver wishing to turn left during a permissive signal phase (i.e., while facing a green ball traffic signal) who turns into the path of an oncoming vehicle or into pedestrians crossing the driver's path to the left, due to limitations in parafoveal attention/UFOV and in the ability to share attention. This problem was associated also with intersections 2 through 8, only to a lesser degree. In these instances, the driver needs to watch but one lane of opposing traffic, as opposed to the more complex designs in intersections 9 through 15, which require scanning two or three lanes of opposing traffic.

Intersections 4 through 8 received a Total Criticality value of 9 for an older driver wishing to proceed straight through the intersection after stopping at a stop sign or for a red flashing signal. The error associated with this maneuver at this set of intersection types is entering the path of a vehicle approaching from the left, due to gap estimation problems. The likelihood of a crash with traffic approaching from the right is reduced at these five intersection types, given that the driver approaching from the right may be able to compensate for the older driver's error quicker than a driver approaching from the left, as it is the left side driver's lane that the older driver would enter first (small approach angle). If a crash occurred under these circumstances, the older driver would be cited with failure to yield.

Intersection type 3 also received a high Total Criticality value (9) for an older driver turning right on a leg controlled by a stop sign or flashing red light. The error is entering the path of a vehicle approaching from the left, due to a difficulty in estimating gaps.

All the intersection types received a Total Criticality value of 9 when an older driver is faced with a traffic signal displaying a steady yellow ball. The error the older driver is likely to commit is stopping unnecessarily, due to extreme caution; this behavior can create a conflict with a following vehicle. The older driver thus then becomes the victim of a rear-end crash. Potentially, this could also result in the rear-ending vehicle pushing the older driver into the intersection, creating a conflict with traffic approaching on the cross street. Similarly, stopping unnecessarily for a yellow arrow at the intersections where this operation would be present (all intersection types except 1 - 4 and 15 - 16) due to extreme caution or uncertainty as to the next signal phase (red or unprotected green) would be more likely to occur with a yellow arrow than with a solid yellow ball, but less likely to result in a crash, rendering a total criticality rating of 8 for maneuvers during the yellow arrow phase.

The remaining problems identified in the task analysis were given Total Criticality Ratings of 6 or less, rendering them less of a priority than those discussed in detail above, in that they would be likely to occur a maximum of 25 percent of the time, or result in a crash a maximum of 25 percent of the time the error occurred.

In conclusion, a number of older driver intersection negotiation problems have been prioritized through this task analysis. These results establish a basis for comparing the performance of different drivers across different intersections, classifying a "unit of analysis" (in relating functional status to driving behavior) according to the physical features and traffic operations that characterize the situational demands upon the individual.

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