

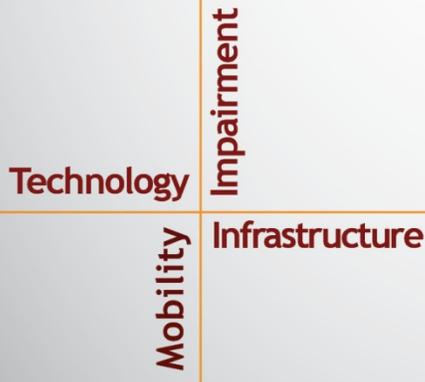
NSTSCCE

National Surface Transportation
Safety Center for Excellence

An Exploration of Driver Behavior During Turns at Intersections (for Drivers in Different Age Groups)

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Submitted: June 23, 2015



ACKNOWLEDGMENTS

The authors of this report would like to acknowledge the support of the stakeholders of the National Surface Transportation Safety Center for Excellence (NSTSCE): Tom Dingus from the Virginia Tech Transportation Institute, John Capp from General Motors Corporation, Chris Hayes from Travelers Insurance, Martin Walker from the Federal Motor Carrier Safety Administration, and Cathy McGhee from the Virginia Department of Transportation and the Virginia Center for Transportation Innovation and Research.

The NSTSCE stakeholders have jointly funded this research for the purpose of developing and disseminating advanced transportation safety techniques and innovations.

In addition, it is important to acknowledge that this project included the completion of a master's thesis by Sudipto Aich at Virginia Tech, and this final NSTSCE report draws heavily from that thesis.

EXECUTIVE SUMMARY

Within the set of all vehicle crashes that occur annually, intersection-related crashes are overrepresented. The research conducted here used a two-phased approach to study driver behavior at intersections using a naturalistic paradigm. In Phase 1, the behavior of teen, middle-aged (i.e., parents of the teens), and older drivers (71–85) was compared for left turns at three types of left turns across path (LTAP) intersections. Phase II was a follow-on effort focused more narrowly on a single T-intersection, but it included both left and right turns.

A data-mining algorithm was used to process data which were aggregated from two different naturalistic databases in order to obtain instances of unprotected turns at the same intersection, as well as instances from a comparison protected turn at a signalized intersection. Several dependent variables were analyzed, including visual scanning measures, head-turning measures, driving-behavior measures (speed approaching and driving through the intersection), and gap-acceptance and -rejection time.

Results from Phase 1 showed that visual-processing patterns were uniquely affected by turn-specific variables. Unprotected turns led drivers to behave differently than did the comparison protected turn. In addition, the two types of unprotected turns also had different effects on driver visual processing. Scan patterns were affected by the different zones of a turn (i.e., initiation, conflict, and completion zones), each of which imposes different information-processing requirements. During the zone of initiation, one of the factors that matters is whether or not there is a stream of oncoming traffic, and whether there is any control signal or signage to assist the driver with passing through it. These factors affect glances made by drivers as they prepare to turn. Glance durations in the zone of initiation lengthened with the need to estimate gap lengths and with the need to extract information about the safety of proceeding (e.g., when there is no control but there is oncoming traffic, gap estimation must be performed and driver glances lengthen as drivers try to estimate and select a gap through which they can safely turn.)

On the other hand, the proportion of glances to the forward area increased for drivers within the conflict zone to over 90%. Within the conflict zone there is a need for drivers to both look at the path along which the vehicle is being steered (the turn path), while at the same time some need to ensure that threats to safety are not present. This affects the locations to which glances are directed. If there was no oncoming traffic, glances were directed to areas of perceived threat (from the stream of traffic approaching from the right), at least for older drivers making left turns in the T-intersection with stop-sign-only control. During the zone of completion, there was a need to look at the new forward path of travel, and possibly an increased need to check the rear view to be sure that the turn was completed without creating an undue threat from a vehicle closing rapidly from the rear.

In Phase 1 there were suggestions of age-group effects and differences. Some were statistically significant and some were not (but the power to detect differences between age groups was limited by power, since this variable was represented by the fewest observations in the experimental design). Age effects on glance patterns were not strong, but there were some subtle suggestions of differences in some conditions. Visual scanning differences by age did not appear to be as simple as studying one intersection and one turn type and then generalizing findings across age. Rather, visual processing appeared to be affected by specific factors unique to

different types of intersections (such as the presence or absence of signals protecting turns, the geometry of the intersection—whether a three-way T-intersection with no oncoming traffic stream or a four-way with an oncoming traffic stream—and perhaps other factors). However, there were definitive age-group effects seen with head turning. The Phase 1 results on head turning suggested that older drivers scanned more narrowly and that they strategically oriented their scans in the direction of greatest threat for certain types of unprotected left turns (as compared to middle-aged and younger drivers, who scanned more broadly and oriented their heads differently during information gathering at turns of certain types). These findings appear consistent with some of the key findings from Bao & Boyle (2007, 2009). Further, these head-turning results provided insight into why the results from glance analysis were more subtle than definitive, specifically because the orientation of head positions was only slightly turned, thus leaving the direction of eye gaze within the spatial area defined as “forward” by glance-coding criteria. Thus, eye-glance data alone would not have revealed the subtle differences in attentional allocation unless head turning had been analyzed as well. Finally, there were also age-group effects in driving behavior, with older drivers proceeding through the intersection turns at slower speed, especially when an intersection was unsignalized.

Results from Phase 2 replicated those from Phase 1, with the longest glance durations directed to the forward path area. Similarly, proportions of glance to different areas replicated the findings from Phase 1. For left turns, most driver groups had a similar distribution of glances by location for this T-intersection, with the forward-looking glances constituting almost half of all glances, followed by glances through the window areas. However, older drivers showed a higher proportion of glances to the right, indicating a strategic shift of attention toward the right that was consistent with that suggested by the head-turn analysis done in Phase 1.

Link analyses done on the visual scan patterns of drivers indicated that older drivers and middle-aged drivers had more-organized and more-strategic visual scans of the intersection during turns, whereas young drivers had less meaningfully organized scans that were less strategically connected to information needed for the turns. While middle-aged drivers and younger drivers scanned broadly, older drivers utilized a narrower scan that was oriented slightly toward the right (for a left turn) — perhaps indicating attention to gap selection and threats in the stream of traffic into which they were merging. The same was true for the right turn, but with attention shifted toward the left (to gauge gaps in the stream of traffic into which the right turn was being made).

Visual entropy analyses showed that active visual scanning (to a larger number of areas) increased for all age groups when traffic was present (vs. absent) during the turn, but this increase was most pronounced for younger drivers. Not significant, but approaching significance, were differences in gap-acceptance times, with the older drivers waiting for longer gaps through which to make their turns compared to the younger teen drivers. Also, peak speed differed among drivers of the three age groups (older, middle-aged, teens) in the presence of traffic in the intersecting streams while negotiating a left turn. Significant differences were observed for peak speed and average speed during a left turn, with older drivers using lower speeds throughout intersections, and completing their turns at lower speeds than other age groups. These slower speeds may have resulted from a desire to be more careful (risk aversion) and/or from a need for more processing time. However, they may have unfortunately also put older drivers in the intersection and in an area of risk for a longer period of time. (Young drivers drove at higher speeds and completed their turns at higher speeds).

Together, these findings suggest that the behavior of older drivers is at least partly strategic in nature (e.g., the narrowed extent of scan, with a rightward orientation, the use of slower speeds). The changes in scanning exhibited by older drivers appear to be more specific, more focused “versions” of the visual scanning typical of middle-aged drivers, tuned specifically to areas of highest threat during turns. However, this may lead to some neglect of other areas that, while perhaps less salient, are still very important and if entirely neglected could contribute to crashes during turns (e.g., possibly impacts with unnoticed traffic or pedestrians that might be present in these areas). In addition, it is still possible that age-related changes in perception and cognition may be contributing to some aspects of these differences in visual scanning and behavior at intersections.

What these changes in older drive behavior suggest about possible countermeasure development is still difficult to identify, especially given that scanning strategies appear to be affected by intersection-specific features (i.e., geometries, clutter, traffic densities, etc.). However, any in-vehicle support for gap estimation that may become possible, or warnings about cross-traffic or pedestrians or objects that may be present in areas that are infrequently scanned, are perhaps areas of active safety assistance that could be explored.

For younger drivers, it may be possible to coach or train improved visual scanning of intersections during turns. The sequence of areas viewed may be something that could be “taught” through appropriate sequences of directed video or other types of appropriate training that are designed to facilitate learning about hazard recognition.

In summary, the findings from this research have extended the understanding of how drivers behave as they negotiate turns at intersections. As more research is done in the future, it will be important to continue to use naturalistic data. It is hoped that some of the new methods that were created as part of this research program will help facilitate such efforts.

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LIST OF KEY TERMS, ABBREVIATIONS, AND SYMBOLS

Signalized Intersection

Signalized intersections are those that offer signaling devices (usually in the form of traffic lights) to control competing flows of traffic. Typically, a green light allows traffic to proceed in the direction denoted, if it is safe to do so.

Protected Left Turn

A protected left turn is a left turn that is controlled—or signaled—by a separate green arrow light on a traffic light.

Unprotected Left Turn

An unprotected left turn is any left turn that is *not* signaled by a separate green arrow light on a traffic light, specifically one occurring at an intersection *without* a dedicated left-turn light; for example, one occurring at an intersection with a stop sign or at an intersection with no signage.

Unsignalized or Uncontrolled Intersection

An *uncontrolled intersection* is one where no traffic lights or signs are used to indicate the right-of-way. These intersections are typically found in either residential neighborhoods or in rural areas.

CHAPTER 1. INTRODUCTION

Turns at intersections have long been recognized as a source of difficulty for both newly licensed teen and other young drivers, as well as for senior drivers, due in no small part to the opportunity afforded by them to put vehicles on potential collision paths. In 2007, 2.4 million vehicle crashes were intersection-related. This was fully 40% of the total number of reported crashes, yet intersections constitute only a small part of our entire roadway system. This overrepresentation of intersection crashes relative to the total number of crashes makes driving behavior at intersections an important traffic safety issue (Federal Highway Administration, 2009). Risk, of course, varies as a function of intersection type (signalized vs. unsignalized), and type of turn (left vs. right, and the degree of protection provided by signals or signage), among other factors. According to the Federal Highway Administration (FHWA), drivers over 65 composed 12.4% of the population, but these individuals were overrepresented in intersection fatalities by a factor of 2:1; individuals over 85 were overrepresented by a factor of 3:1. While some of this overrepresentation of older drivers may be due to their increased propensity for at-fault crashes in these types of driving scenarios, it is very likely that these higher-than-expected fatality statistics are also representative of the increased fragility and susceptibility to injury so often seen in this population.

Staplin, Lococo, Byington, and Harkey (2001) reported that 48% to 55% of all fatal crashes involving drivers aged 80 years or over occurred at intersections, a rate more than twice that for drivers under the age of 50 years (23%). Similarly high percentages (45%) have been reported for newly licensed teen drivers (Braitman, Kirley, McCartt, and Chaudhary, 2007). This is not surprising when one considers the relatively complex set of tasks comprising intersection negotiation, especially unprotected turns across path (UTAP). During UTAP crossings, drivers must perform and integrate over time the visual and cognitive tasks associated with this maneuver. These include, at least, (1) monitoring signal state (when a signal is present); (2) estimating sufficient gap time, as necessary; (3) monitoring for pedestrian presence; and (4) negotiating the intersection with sufficient speed with respect to the estimated gap (after Gordon, Nobukawa, Barnes, and Goodsell, 2009). It would be expected that inexperienced drivers and senior drivers with reduced functional abilities might have difficulties successfully integrating these tasks within the time constraints presented.

It is expected that this issue may become more serious in the future, as the population of older drivers has increased over the past decade and is projected to increase by almost twofold in the next decade. Such shifting demographics have provided impetus for understanding and creating a transportation environment that assists this age group, especially in negotiating intersection scenarios.

Recent research has explored the possible factors that may contribute to age-related differences in driver behavior at turns. Among these are the following:

1. Visual scanning by older drivers is different from that of other drivers.
 - a. At intersections, particularly after the act of turning has been initiated (Romoser, Fisher, Mourant, Wachtel, & Sizov, 2005; Romoser & Fisher, 2009; Bao & Boyle, 2007, 2009)
 - b. When approaching hazards (Fildes, Charlton, Koppel, Andrea, & Hammer, 2006). Fildes et al. (2006) found age-related differences in scan patterns for hazards in simulator studies.
2. Cognitive changes occur with age and may be relevant for these maneuvers, including:
 - a. Slowed processing speed with age;
 - b. Reduced top-down inhibition (which affects the ability to selectively attend) and slowed top-down facilitation of visual activity with age (Gazzaley, Cooney, Rissman, & D'Esposito, 2005; Gazzaley et al., 2007).

Additional possibilities include differences in knowledge-based strategies (between older and younger drivers), differences in risk tolerance, and many more. Some research has provided more specific insight into the nature of problems at intersections. Preusser, Williams, Ferguson, Ulmer, and Weinstein (1998) reported that within the crashes they analyzed, relative crash risk was particularly high for older drivers at uncontrolled and stop-sign-controlled locations; when traveling straight or when just starting to enter the intersection; and when the specific behavioral error in the crash was a failure to yield.

McGwin and Brown (1999) reported that the youngest and the oldest drivers were more likely to be considered at-fault in crashes at intersections. Additionally, they found that older drivers were over-represented in intersection crashes and/or those involving failure to yield the right-of-way, unseen objects, and failure to heed stop signs or signals. McGwin and Brown (1999) pointed out that older drivers tend to be averse to risk, and that this is a strength, but one which may be offset by perceptual problems and difficulty judging and responding to traffic flow. In contrast, they cite that the primary problem with the young is risk-taking and lack of skill. Another possible mediating variable is lack of experience, which may contribute to difficulties for young drivers, especially if it plays a role in the identification of threats or hazards during visual scanning.

Among the studies that have been done to date are two that are particularly relevant for the research work reported here: those by Bao and Boyle (2007, 2009). In these studies, Bao and Boyle conducted on-road controlled experiments of left and right turns (vs. driving straight) at two different rural expressway intersections that contained a median, one that had a high crash rate and one that had a low crash rate.

In the first study, Bao and Boyle (2007) studied a small sample of 10 older drivers and 10 middle-aged drivers. They examined number of glances and a variable called "search time." Both of these variables were examined in the period of approach to the intersection, defined from a point 34 meters prior to the stop sign controlling the intersection to the point defined as the entry point to the turn (identified as the driver's first depression of the accelerator pedal after

having been stopped at the stop sign). They found that the type of turn or maneuver (left, right, or straight) had a significant effect on the number of eye glances made by drivers during this period, and found that this effect was further modified by a significant interaction with intersection type (high- vs. low-crash intersection), such that drivers made significantly more glances prior to driving straight across the high-crash intersection (vs. any other condition). Notably, no significant differences in glance patterns were found between age groups. There was a significant difference between older and middle-aged drivers in the variable called “search duration,” which indicated that older drivers spent significantly less time than middle-aged drivers in the period between the 34 meters prior to stop, being stopped, and the moment at which they accelerated to enter the intersection for their maneuver. Although no interaction with traffic volumes was reported, the graphically displayed means suggest that this difference between older and middle-aged drivers was most pronounced for higher traffic volumes (and that the difference was absent when no traffic was present). This would suggest that there are mediating factors influencing the search time allocated by older drivers prior to making a turn, but it is unknown what these factors may be. For example, one possibility is that older drivers felt hurried by the presence of surrounding traffic. But there may well be other factors that may have contributed to their search times under higher traffic volumes (e.g., potentially different vehicle speeds in the process of slowing to a stop that could have affected search time, or feeling pressured by the experimental setup and the presence of an experimenter in the vehicle).

In the second study by Bao and Boyle (2009), the same maneuvers (left turn, right turn, and straight across driving) were again studied at two median-divided rural expressway intersections (one with higher crash incidence, and one with lower crash incidence). In this second study, 20 drivers in three age groups were studied: younger (18–25), middle-aged (35–55), and older (65–80). The focus in this study was specifically on visual scanning, which was measured in two ways. First, it was measured by visual sampling toward the left and right (and also rearview mirror) based on guidelines related to degrees of head turn.¹ Secondly, it was measured by a calculation of entropy (or randomness/organization in the visual scans). Results indicated that the scan patterns of older and younger drivers had less breadth (with sampling of fewer areas) before executing a maneuver relative to middle-aged drivers. This corresponded to lower entropy scores. They also noted that older drivers exhibited a significantly smaller proportion of visual sampling to the left and right during the intersection negotiations (as compared to the other age groups). Bao and Boyle (2009) interpreted this set of results as indicating that older drivers have a greater likelihood of missing an unexpected event during the turn. (Bao and Boyle, 2009, also used visual sampling of the rearview mirror as an indicator of attentiveness to the road environment based on prior literature, though its relevance during the periods that drivers prepare for and execute turns is not clear.)

Several additional findings from the Bao and Boyle (2009) study are worth noting. First, they found that drivers tended to exhibit a higher proportion of visual scanning to the side opposite the direction of their turn (for both right and left turns). While Bao and Boyle (2009) focused on the negative implications of this, we would point out that there is some adaptive value in this behavior, since it is the traffic stream coming from the side opposite from the direction of turn in

¹ Though it is not clear from Bao and Boyle (2009), this measure may have been based on scoring of glances, with degrees of head turn used only to define glance locations (or areas of gaze), based on a premise that head turn and glance tend to correspond. This topic comes up later in this paper on p. 35.

which a gap must be found that is large enough to turn into, and it is also from this side that traffic may strike for both turn types if an error is made. (Of course, for the left turn, not only must the traffic to the right be sampled, but also any traffic to the left, since that stream of traffic must also be crossed. However, in some intersections that stream of traffic is under the control of a separate signal or sign). Second, they found a significant interaction on visual sampling between turn/maneuver, intersection type, and age group. This indicates that intersection-specific factors, as well as turn-specific, mediate the visual scanning behaviors of drivers (within different age groups).

However, while individual studies have contributed individual findings about age-related changes, it does not appear that these findings have been pulled together as part of an explanatory framework for application to age-related factors in visual scanning and selective attention (or for application to visual scanning of intersections by novice drivers). While there are many hypotheses about the myriad changes in visual processing that occur with aging, as well as age-related changes in cognitive processing that may affect the ability to selectively attend, there is also recognition that with age comes additional experience, and this may lead to increasingly strategic focusing of attention and/or behaviors during driving—including during turns. So the particular way in which such factors combine to place older drivers at higher risk of crash and fatality during turns has yet to be understood. And, on the other end of the age spectrum, it is interesting that novice drivers have also been reported to show less mirror scanning and reduced scanning for hazards (e.g., Lee et al., 2008). However, while these effects may arise from the same underlying cognitive processes (e.g., selective attention) that may contribute to difficulties for older drivers, they may arise for altogether different reasons (e.g., from a lack of knowledge for younger drivers that may lead to an inability to generate appropriate top-down, expectation-based facilitation of eye movements to probable locations of hazards at intersections).

Most importantly, while some of the studies in the literature on driver behavior at intersections have been done on the road, others have done in driving simulators. It would be useful to discover whether key findings from these approaches can be replicated in naturalistic driving studies. At this point, little or no research in the published literature has been conducted on behavior during turns using naturalistic data (with the exception of one observational study using cameras mounted external to vehicles at an intersection). If naturalistic data were to confirm findings on visual scan patterns of older and younger drivers at intersections, and additional work were done to ascertain the causes of observed differences in visual scan patterns, then such research may facilitate the identification of countermeasures for assisting these two groups of vulnerable road users with the negotiation of intersections.

Therefore, in late 2009, a program of research was undertaken to use naturalistic data to explore the behavior of drivers within different age groups while turning at intersections. This research was conducted in two phases and is described within this report.

PURPOSE AND STRUCTURE OF THE RESEARCH REPORTED HERE

The purpose of the research reported here was to determine if the behavior of older drivers or younger drivers differs from that of middle-aged drivers during the negotiation of turns at

intersections in natural driving. Of particular interest were visual scanning and selective attention behaviors during left turns.

The research was conducted in two phases using naturalistic driving data.

In Phase 1, the behavior of younger, middle-aged, and older drivers was examined for left turns at three types of intersections:

- Signalized, protected intersection
- Unsignalized, unprotected intersection with stop sign
- Unsignalized, unprotected intersection with no signage and no through traffic

The primary focus was on left turns across path at these intersections.

In Phase 2 of the research, the study focused more narrowly on a single intersection type, a T-intersection, but included both left and right turns. This was ideal because it controlled for certain features of the intersection that would otherwise vary between intersections and which might affect driver scanning behavior.

This report first describes the methods that were used to create a database of naturalistic driving data from two existing sources and to identify matched epochs of turns at matched intersections. Following the methods section, the analysis and results of Phase 1 are presented and discussed, and then the analysis and results of Phase 2 are presented and discussed. The report concludes with a general discussion of the findings on age-related differences in turn behavior and their implications.

CHAPTER 2. METHODS

The research undertaken here used existing naturalistic data from two different studies. It developed methods to search through these two large databases and extract turns of the same type (left or right) made by drivers who not only drove through the same intersection but entered them from the same direction and turned onto the same road when leaving the intersection.

OVERVIEW

This research on driver turning behavior at intersections drew upon two existing naturalistic driving data sets that were collected within the same general vicinity: the New River Valley area of Virginia. They were the *Older Driver Study* (Antin, Lockhart, Stanley, and Guo, 2012) and the *Naturalistic Teen Driving Study* (NTDS; Klauer et al., 2011). Relevant data for turns at intersections were extracted from these two databases for three age groups of drivers: older, middle-aged, and younger teen drivers. The data for older drivers were drawn from the Older Driver database, and the data for both younger and middle-aged drivers were drawn from the NTDS (the middle-aged drivers were selected from among the parents of the teen drivers in the NTDS). Additional details are discussed in the following sections of this chapter. However, first some brief background is provided about each of the two driving studies that served as sources of data for this study.

DATA SOURCE #1: THE NATURALISTIC TEENAGE DRIVING STUDY

The NTDS, also called the “40 Teen Study,” examined a group of newly licensed teenagers for 18 months after licensure. The final sample in the NTDS included 42 newly licensed teen drivers who were 16 years of age or older, who were studied during their first 18 months of independent driving. The study also included the parents of the teens as secondary drivers. Table 1 shows the mean and standard deviations of age for the teen and parent participants. As mentioned previously, the middle-aged group of drivers for the study reported here were drawn from among the parents of these teens, but for the purposes of this research steps were taken to ensure that no familially related teen and parent appeared in the same experimental block. Overall in the NTDS, 33 vehicles were instrumented (and these represented 17 different vehicle makes). At the conclusion of the study, teens and parents had driven approximately 500,000 miles in nearly 102,000 trip files (from ignition on to ignition off). On average, the teenagers drove 367 miles per month for the duration of the study period.

Table 1. Teen and parent participant age information by cohort and gender.

	Males		Females	
	Age (years)	S.D.	Age (years)	S.D.
Teens	16.4	0.3	16.4	0.4
Parents	49.4	5.3	45.7	5.1

DATA SOURCE #2: THE OLDER DRIVER STUDY

Twenty individuals were primary participants in the year-long study, which required the participant vehicle to have been instrumented for that period. Table 2 tabulates the age range and

mean age of participants by gender for the older driver study. In total, the study collected over 30,000 trip files (ignition on to ignition off), which represented over 4,600 hours of driving data.

Table 2. Older driver participant age information by driving group and gender.

GENDER	AGE (years)	
	Age Range (n)	Mean Age (s.d.)
Male	70–84 (14)	77 (4.6)
Female	71–85 (12)	79 (4.3)

DATA ACQUIRED WITHIN THE STUDIES

There were three primary reasons for selecting these two driving databases for use in this research on intersection behavior: (1) they included a wide range of differently aged drivers with varying levels of driving experience, (2) they were both collected in the same geographical area, which permits specific intersection crossing comparisons, and (3) the data collected in both studies were virtually identical.

All vehicles across the two studies were equipped with a data acquisition system (DAS), which included an array of cameras, front radar, and other sensors to acquire and record data to a central unit, typically located in the vehicle’s trunk. The data collected included variables such as vehicle speed, distance to forward vehicles, turn signal status, and lane position. Each vehicle was equipped with four cameras. These provided a view of the forward roadway, the driver’s face, an over-the-shoulder view of the driver’s arm and hand movements between steering wheel and devices (or other objects) within the vehicle, and a view out the rear of the vehicle. These four video images were time synchronized and combined into one, quad-split image, which was recorded continuously for later analysis.

MASK Software

Data on head-turning behavior in the naturalistic studies used here were acquired through an automated head tracker, called the “MASK,” that was developed by VTTI and later deployed within the Second Strategic Highway Research Program (SHRP 2) study. The mask is a machine-vision based software that uses a mostly classical style approach to match a 3-D triangular mesh onto the face video of participants, tracking the position and rotation of the participant’s head in space. Its functionality is illustrated in Figure 1.



Figure 1. Photo. A photo illustration of VTTI’s MASK head-tracker.

While the MASK was used in an exploratory application to acquire data in both the NTDS and Older Driver study, its data had never before been analyzed at the time of this research project on intersection behavior. Therefore, it was necessary to create methods to process and analyze the MASK data. It should be kept in mind that these efforts were (and are) deemed exploratory until a more in-depth verification of the MASK head-turn data is undertaken.

For this work, methods were created for taking the raw MASK data from each driver and vehicle and calibrating it to a common coordinate system (representing areas of interest in the forward roadway toward which the head and eyes might be turned for viewing). It was necessary to do this because the face camera is installed in each driver's vehicle at a slightly different location relative to the driver's face and gives its output for driver head position in x , y , and z coordinates that are referenced to its location in the driver's vehicle. Unless these coordinates are translated to a common coordinate system, the data from each driver have a different meaning. Therefore, methods were applied to translate the MASK output to a common coordinate system, thus recoding it for analysis. This was done using the value for "forward" that was output by the MASK and mapping it to the position of "true forward" in a common coordinate system. MASK data were only used when the system-output confidence indicator met a minimum criterion. It should be noted that calibration and recoding of the MASK data (even using these procedures) was nontrivial. Developing techniques with which to validate the calibrations and mappings to the environment continues to be a technical challenge, but the initial findings here are encouraging. Efforts to verify this use of the MASK data are expected to continue.

DATA MINING AND REDUCTION

Figure 2 provides a diagram of the process that was followed in merging and then mining these two large databases in order to construct smaller data sets tailored to the analysis objectives of this research on driving behavior at intersections. Individual components of this process are described below.

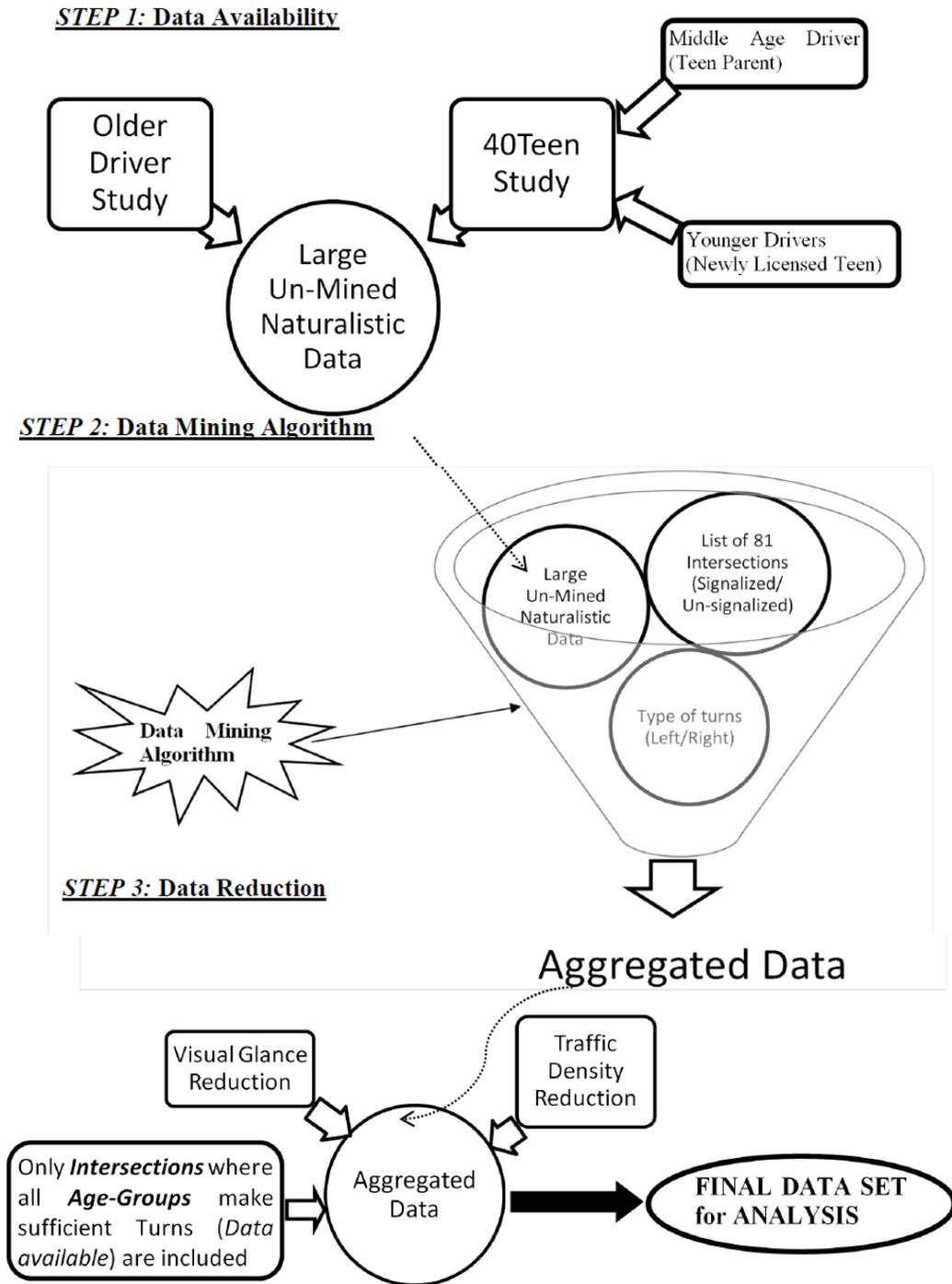


Figure 2. Diagram. Process flow for merging databases, mining the aggregated data set, and constructing the final data set for this study. Reprinted from Aich (2011).

Data Set Merging, Mining, and Construction

It was necessary to carry out a number of data aggregation, sorting, and mining procedures to find and develop data files of interest for this study's objectives. This process was nontrivial, and the methods developed are themselves an important output from this project. They were developed by Aich (2011). Therefore, they are described in some detail below.

Initial Data Aggregation and Sorting

Since this research used naturalistic data from two different data sets, it was first necessary to aggregate them and then find and extract the relevant epochs of data that were pertinent for the specific research questions addressed here. Since the objective was to observe driver behavior during turns made at intersections, this first step involved identifying a common geographic location that was shared by most of the participants (e.g., an area where most of their driving took place, typically a zone near participant residences and work areas) so that matching intersections could be identified. Such a common geographic zone was created by researchers at the Virginia Tech Transportation Institute (VTTI), along with a list of intersections within it, using geographic location, traffic probability, and crash propensity information. Eighty-one intersections were identified and listed with their coordinates in latitude and longitude. This list included both signalized and non-signalized intersections.

Once all these intersections were identified, the next step was to examine the naturalistic databases and find all driving trips within them that were made across these 81 intersections within the two studies. The next section describes how an algorithm was developed to accomplish this objective through automated processing of the data. However, first it is necessary to discuss how the intersections were labeled so that they could be used in the next stage of code development and use.

Geospatial coordinates were used to label the intersections. For each intersection, individual branches or legs of the intersection were also geo-tagged. In other words, each intersection was identified using a set of points, which were used to determine not only whether a driver drove through the intersection but also from which direction a driver approached the intersection, proceeded through the intersection, and exited the intersection. Even a simple intersection could easily have twelve different such combinations (i.e., approaching from the west and exiting to the north, south, or east, and the similar options when approaching from either of the other three directions).

Figure 2 shows how a four-way signalized intersection was geo-tagged and labeled. In this figure, the numbers enclosed in bubbles represent each of the various legs of the intersection, where the numeral "0" labels the center of the intersection and the numeral "1" labels the northern road or leg that connects to the intersection's center. The other number labels assigned to the other legs of the intersection increase in a counter-clockwise fashion (moving around the center point of the intersection from the northern leg), from "1" to "2" to "3" to "4."

Latitude and Longitude of a Point

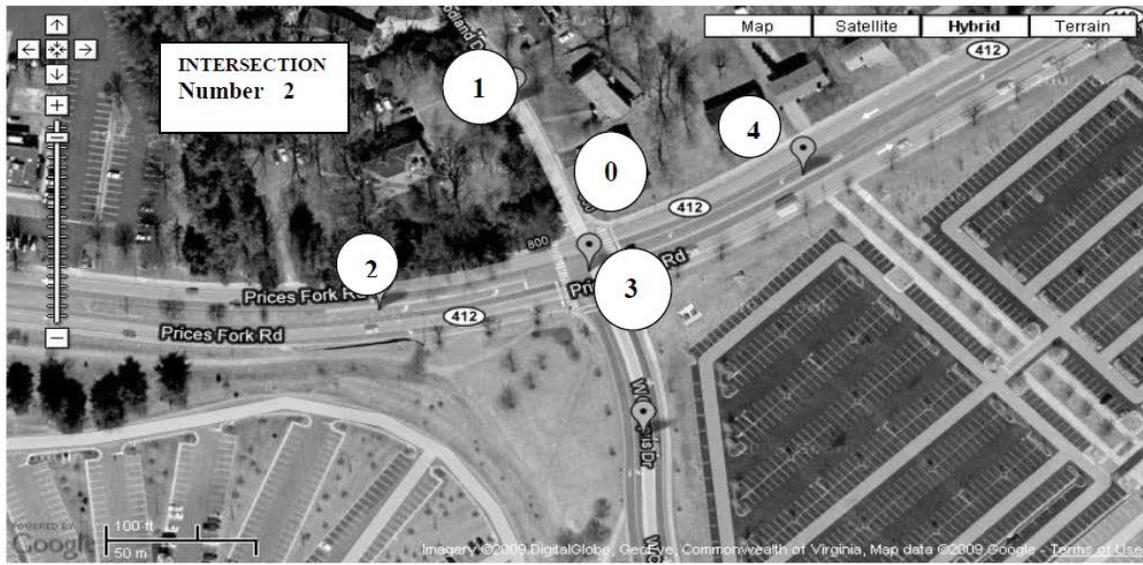


Figure 3. Photo. Latitudinal and longitudinal GPS coordinates displayed as numbered nodes on a map that was used for the purpose of identifying instances of any driver driving through an intersection.

This type of tagging was necessary to differentiate between drivers who took different routes through the same intersection. For example, one driver could approach the intersection from the north, i.e., entering from the leg labeled “1” and pass through the intersection, making a right turn towards the west onto the leg labeled “2.” This route would be identified as Route ID 102 (where the digits of the identifying code represented the entry leg, the center of the intersection, and the exit leg of the intersection). In contrast, another driver could approach from the south, using the leg labeled “3,” and make a left turn towards the west, onto the leg labeled “2.” This would be labeled Route ID 302. (In the following section, a description is given of how the data mining algorithm used these Route ID numbers for the purpose of this research.) This tagging system was important because the visual scene and driving scenario that a driver processes when turning left from Leg 1 to Leg 4 looks visually different from that seen when turning left from Leg 3 to Leg 2 (or from other legs of the intersection) due to differences in roadway, traffic flow, landscape, and roadside features. Thus, it may be scanned differently for reasons related to the scene (rather than for reasons attributable to drivers or their behavior). Therefore, in order to examine differences between driver age groups in visual scanning and other behaviors, it was critical that intersection and turn type (leg-to-leg) be matched.

Data Mining Algorithm Logic

To facilitate the search for matching turns in the naturalistic data, a table was created in which all the intersections and their legpoints were listed (with accompanying geospatial Global Positioning System [GPS] coordinates for each) for each driving trip file in the whole data set from both studies. The trip file contained the GPS coordinates that provided information about the route taken by the driver for that trip. An algorithm was then formulated to compare each individual trip file to the list of 81 intersections in order to determine whether a driver went through any of the listed intersections in that trip. The logic for determining this was based on calculating the distance of each set of GPS

coordinates from the driving trip to all the intersections. For example, a driving trip that contained 300 seconds of data was composed of about 900 continuous GPS coordinates (because GPS was recorded at 3 Hz), so the distances between each of those 900 points and the 81 intersection points were calculated. Whenever this distance was under 50 feet, it was stored in a local repository as a likely match to one of the intersections. This application of the algorithm reduced the huge amount of driver data from each database to a much smaller and more focused data set. Then, to gain further information as to what kind of turn maneuver the driver made, the algorithm arranged the data in order of timestamps, sorting the observations in the order in which the legpoints were crossed. This resulted in the assignment of a Route ID code to each trip. Once this was done, trained analysts examined the video to confirm whether all the selected, reduced files reflected the intersection scenarios that the algorithm suggested.

When this was completed for all files, one further analysis was needed, which was also performed by a human analyst, who checked to determine whether any teens and parents from the NTDS were related within any blocks of the experimental design to which extracted data files had been assigned for analysis. If they were, the analyst would try to replace the data files from one of the participants with trips from a driver who was not related. Whether or not this was possible depended upon how much data remained in the pool for non-related participants. In some cases, it was necessary to eliminate one of the files from a familiarly related individual. This sometimes exacerbated an issue with unequal sample sizes between cells of the analysis, which will be discussed later. However, to have the most robust analyses possible of the effects of interest, it was desirable to strive for independence between observations within the cells being analyzed for an effect—and the literature has shown that there can be some parental influences on teen driving habits (which implies potential non-independence of observations). Therefore, it was deemed best to eliminate all familial relationships that could potentially confound or influence effects on the driving behavior variables of interest in this study at this early exploratory stage.

Once the data mining algorithm was applied to the whole database, intersections with the largest number of turn epochs across all the age groups were identified. In order to have sufficient statistical power, it was necessary to find one or more intersections through which a reasonably sized sample of drivers had all made turns in the same direction of travel through the intersection. Thus, following data mining, a count of turn epochs by drivers was examined. From this, it was determined that the unsignalized intersection through which the largest number of drivers had made turns was an intersection in Blacksburg, VA, specifically where Patrick Henry Drive meets Harding Avenue. Therefore, this intersection was selected for use in the ensuing analyses, which were performed in Phase 1 of the research. In addition, a signalized intersection (at which left turns were protected by a left-turn green arrow) was also selected for comparison purposes.

The unsignalized intersection at Patrick Henry Drive and Harding Avenue is shown below in Figure 3. It is a T-shaped intersection. It has a one-way stop sign, where the traffic that stopped at the stop sign made an unprotected turn into flowing traffic. This intersection posed a unique problem for drivers coming to a stop there and making a left turn into flowing traffic. Unlike other intersection scenarios, where drivers often have the right-of-way to complete a turn which is governed either by a signal or a stop sign at all corners, this intersection did not provide a way for drivers at the stop sign to establish a right-of-way to enter flowing traffic. Drivers had to stop and then wait for a gap large enough to accommodate a left turn into the traffic flows going in

both directions. Figure 3 shows some pictures of the intersection and turns that drivers could make into flowing traffic streams. The left- and right turn paths are shown in Figure 4.

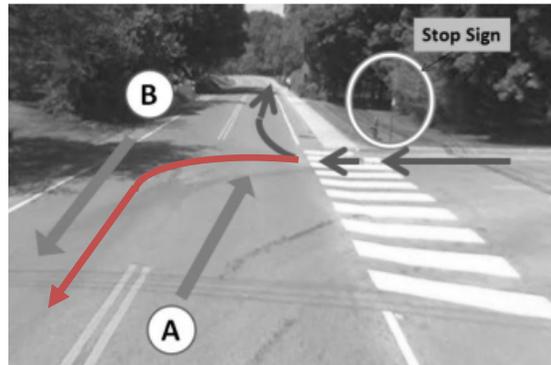


Figure 4. Photograph. The unsignalized intersection selected for this research showing left- and right-turn paths as well as the flow of existing traffic. Base image reprinted from Aich (2011).

In Figure 3, the thin arrows depict the approximate turn path that drivers would typically follow to complete either a left or right turn. It is important to understand that existing traffic (i.e., streams A and B) have the right-of-way, including the scenario where a vehicle traveling in the B direction chooses to make a left turn at the intersection which would also conflict with the subject vehicle desiring to make a left turn to merge into the traffic flow in direction B. For right turns, subject drivers will mostly be concerned with the A traffic stream. For drivers making a left turn, careful attention will need to be given to both the A and B streams.

The initial number of total participants and individual trips made through this intersection are shown in Table 3 below. These initial tabulations show counts prior to the elimination of trips that contained broken files, and before eliminating driver trips due to parent–teen familial relationships. The final number of participants that were used for any given analysis varied by analysis and depended upon the individual experimental block constructed to explore each research question or hypothesis. Because the number of participants available in each cell for each analysis is at the lower limit (or in one instance, below the lower limit) required for minimum power to detect differences of a moderate size, every effort was made to maximize data available for each analysis (while still protecting the quality of the data).

Table 3. Data available for the unsignalized T-intersection (prior to elimination of familial relationships, sorting into traffic levels, and removal of corrupt data files). Reprinted from Aich (2011).

Driver →	Teen Driver		Parent Driver		Older Driver	
Turn Type	Unique Participants	Total Number of Trip Files	Unique Participants	Total Number of Trip Files	Unique Participants	Total Number of Trip Files
Right Turn	17	530	12	141	8	43
Left Turn	15	159	7	33	10	31

When the final number of files per condition had been finalized (by eliminating parent–teen familial relationships and corrupt files), the next step was to code the video data for visual glances, gap acceptance, and traffic density.

Data Reduction from Video Images

Once data files had been selected for matched intersections and turns for each phase of this research, the video data from each of the selected turn epochs were then coded by trained video analysts. The procedures used are described below.

Visual Glance Reduction

Video images of glances were obtained from the camera that was focused on drivers’ faces during data acquisition. This video was reduced in a frame-by-frame mode by VTTI reductionists. Analysts viewed each frame of the video and coded the location of the glance at that frame. Glances to the locations listed in Table 4 below were coded (along with three additional codes denoting obstructions or missing video data of different types).

Table 4. Locations of glances scored in this research (from Aich, 2011).

<input type="checkbox"/> Forward	<input type="checkbox"/> Center Stack
<input type="checkbox"/> Instrument Cluster	<input type="checkbox"/> Cell phone/Other personal devices
<input type="checkbox"/> Rearview Mirror	<input type="checkbox"/> Interior object
<input type="checkbox"/> Left Window/Mirror	<input type="checkbox"/> Passenger
<input type="checkbox"/> Right Window/Mirror	<input type="checkbox"/> Eyes Closed
<input type="checkbox"/> Left Windshield	<input type="checkbox"/> Left Window
<input type="checkbox"/> Right Windshield	<input type="checkbox"/> Right Window
<input type="checkbox"/> Over-the-Shoulder (Left or Right)	<input type="checkbox"/> Eye Closure
<input type="checkbox"/> Unknown	

Traffic Density Reduction

The next step in the data reduction process was to evaluate the level of vehicular traffic during each intersection epoch using video from the forward-scene camera. This was done to determine whether and how the presence of surrounding traffic affected driver behavior during the process of making a turn. The convention for coding traffic density from the video of the intersection epochs is shown in Figure 4 for each different leg of the intersection. Pedestrian presence or level of foot traffic was not noted.

The data codes that were used for the initial assessment and coding of traffic density are shown diagrammatically in Figure 4, and their respective definitions are provided in Table 5. A code was assigned based on a count of the number of vehicles that were present in the stream. All counts of other vehicles ahead of the participant were performed while the primary/participant vehicle (P) was at the stop sign waiting to make the turn.

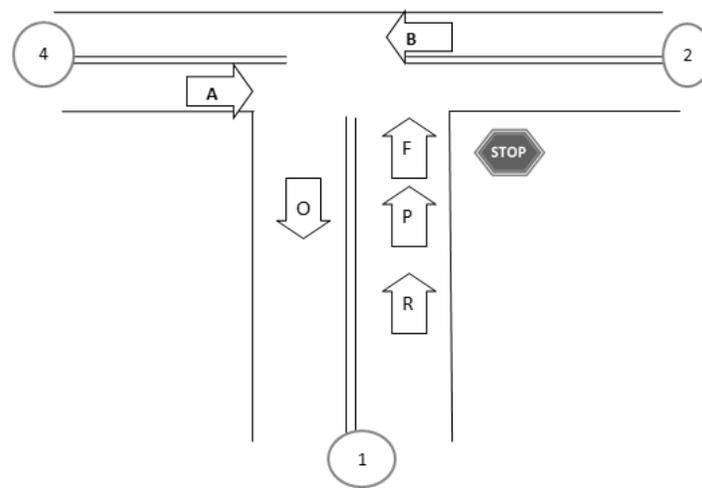


Figure 5. Diagram. An unsignalized intersection showing coding scheme for traffic density (from Aich, 2011).

However, it was found that for a statistical analysis of traffic density levels, there were not enough instances per level to have sufficient power to detect the effects of traffic present at different locations surrounding the participant's vehicle.

Therefore, traffic code levels were subsequently collapsed into two levels in order to increase the number of observations per level. The levels that were used in this two-level approach were the following: (1) the presence of traffic in intersecting lanes and (2) the absence of traffic in intersecting lanes. The definitions of these two levels are given in Table 6. For left turns, the "traffic present" level included all instances that had traffic in the A and/or B stream. For right turns, the "traffic present" level included only those trips that had traffic in the A stream. Finally, instances where there was no traffic in either the A or B stream while making the left turn were coded as "no traffic present," whereas for right turns instances were coded as "no traffic present" only when there was no traffic present in the A stream.

Table 5. Codes used in the initial coding of traffic density at intersections (from Aich, 2011).

CODE	CODE DEFINITION
P	subject vehicle
1,2,4	direction markers (heading)
R	number of cars behind the subject vehicle at the time of departure from the intersection
F	number of vehicles in front of the subject vehicle when it comes to a stop for the first time while approaching the intersection
A	number of vehicles coming from 4 and continuing to head toward 2
B	number of vehicles coming from 2 and continuing to head toward 4
BO	number of vehicles coming from B making a turn toward O
AO	number of vehicles coming from A-4 making a turn toward 1
O	number of vehicles in the opposite lane that passed the subject vehicle for the entire duration of its wait at the stop sign
<i>Note: The code O will be used in instances where it is not possible to assign a vehicle under either AO or BO, i.e., what turn a certain vehicle made</i>	

Table 6. Final traffic density levels used for analysis in this work (from Aich, 2011).

Traffic Levels	Left Turn	Right Turn
Traffic Present	Vehicle present through both traffic stream A and B	Vehicle present through stream A
No Traffic Present	No vehicles through stream A and B	No vehicles through stream A

Analysis Approach and Issues

In selecting methods for analyzing the data, three issues were particularly important. These were (1) issues related to unequal sample sizes, (2) issues related to the selection of univariate or multivariate analysis approaches, and (3) limited statistical power.

Unequal N

When data are extracted from naturalistic studies, it is often the case that there are unequal numbers of observations for different types of conditions. This is because natural conditions do not allow for presentation of a treatment to a sample of participants. Instead, participants are observed behaving naturally. If some subset of them all naturally happen to experience or expose themselves to the condition under study, or generate the behaviors of interest, then those can be identified and used in analyses to assess effects. However, this process (of identifying drivers within a naturalistic study who happened to all experience the same intersection turn or other condition of interest) usually produces unequal numbers of observations across the cells of an analysis (as it did in this study). In other words, more drivers of one experimental category (e.g., more drivers of one age group than another) may drive through a particular intersection of interest.

The first issue in dealing with unequal sample sizes within an experimental design is determining whether the variable of interest (e.g., in the case of this research, the variable of driver behavior at intersections or turn types) itself led to or caused any loss of data from cells (i.e., whether a particular

driver group had a smaller or larger sample size because of an inherent driver behavior that may have confounded the results). In this research, there were more observations for teen drivers making left turns at the selected left turn intersection than middle-aged drivers, and fewer observations for older drivers. However, this was determined to be due to factors unrelated to driver behavior. (For example, more teens were recruited for the teen study than for the older driver study and the intersection selected for the study was nearby the teens' school). However, this was due to participant-recruiting strategies that were entirely separate from this research (and driven by factors entirely outside the current research) rather than due to any factor inherent to driving behavior per se. Therefore, the data with unequal cell sizes were deemed free of problematic confounding and appropriate for use.

A second issue in dealing with unequal sample sizes relates to whether weighted or unweighted means should be used in analysis. In the case of unequal sample sizes, the use of unweighted means is recommended by statistical experts. Therefore, these data were analyzed using statistical packages where unweighted means are utilized (e.g., SAS JMP, SPSS) to calculate least square means.

Univariate vs. Multivariate ANOVA

Univariate analysis of variance (ANOVA) was selected as the most suitable approach for this research. It was applied to each dependent variable separately in order to determine the effects of the independent variables. Although multiple ANOVAs were run, they were few enough in number that there was not a significant concern about an experiment-wise error in detecting significant effects. However, in the event that a significant concern about this should arise, an experiment-wise adjustment to the alpha level can be applied to protect against too many significant results being obtained simply by virtue of the numbers of analyses performed.

Limited Power to Detect Differences

The issue of unequal sample sizes and the sparseness of data in some cells of the experimental designs used for analysis appears to have constrained the power of statistical tests to detect effects under study. However, because this research is the first to have explored these research questions with naturalistic data, there was no a priori way to determine the power needed to detect effects (because there was no historical basis on which to estimate effect sizes or variability on the measures). However, the sample sizes used in this research were very small. Thus, the results of this research must in some instances be regarded as exploratory and suggestive only. In some cases, the analyses revealed statistically significant outcomes but, in other instances, revealed only trends (which may be definitive under circumstances where more data and hence more statistical power are available).

Nonetheless, exploratory approaches have an important role to play in science, along with more definitive hypothesis-testing research that can be applied once exploratory work has opened up new avenues of investigation. For example, descriptive statistics for glance distributions and kinematic ranges can be very helpful quite apart from hypothesis-testing outcomes. In addition, important files and cases can be identified as opportunities. Therefore, the analyses described in the next chapters provide value, though they are (in some instances) exploratory in nature and venture into new areas of technical content using newly available naturalistic driving data. As more data become available, some of the findings that are preliminary here can be reexamined with more robustness using the methods developed for this research.

CHAPTER 3. PHASE 1

This chapter presents and discusses the results from the first phase of the research.

EXPERIMENTAL DESIGN FOR PHASE 1

The experimental design for Phase 1 of this research used a mixed design, with two between-subject variables, Intersection Type (see Table 7) and Age Group (younger, middle, older), and two within-subject variables, Zone of Turn (initiation, conflict, and completion) and Area of Glance (rightward, forward, and leftward).

Dependent variables in three categories were examined:

- For visual scanning behavior:
 - “Proportion of Forward Glances” (Forward)
 - Mean Glance Duration
- For head-turning behavior: Range of Rotation in Y-Dimension
- For driving behavior: Mean Speed

Intersections and Turn Paths Selected for Analysis

For Phase 1, three turns were selected: two unsignalized, unprotected left turns from the same intersection and a protected left turn from a different intersection (for use as a comparison). The two turns at the same intersection followed different turn paths. The third turn was a left turn at a signal offering protection in the form of a left arrow on green. Each left turn was examined in terms of the zone of initiation, conflict, and completion (these zones are defined below in the next section). Table 5 summarizes the characteristics for each turn.

Table 7. Matched turns used for Phase 1 of the research.

Intersection	Turn Path	Description	Driver Participants
6	104	Unsignalized/unprotected w/ no signal/signage, no through traffic	4 Older Drivers (1-4) 4 Middle-Aged Drivers (5-8) 4 Younger Teen Drivers (9-12)
6	201	Unsignalized/unprotected w/ stop sign	4 Older Drivers (13-16) 4 Middle-Aged Drivers (17-20) 4 Younger Teen Drivers (21-24)
20	302	Signalized/protected - control	4 Older Drivers (25-28) 4 Middle-Aged Driver (29-32) 4 Younger Teen Drivers (33-36)

Definition of Zones within Intersections

Intersections were defined in terms of three zones. An overview of an entire intersection, broken into these three zones is shown in Figure 5. In Figures 6, 7, 8, 9, and 10, each zone is illustrated separately, beginning with an illustration of the pre-turn state and ending with an illustration of the post-turn state.

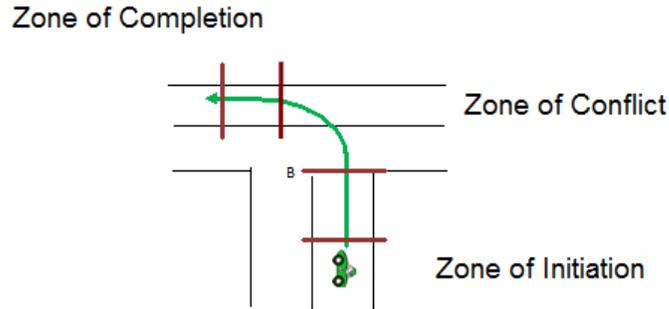


Figure 6. Illustration. Definition of zones within intersections.

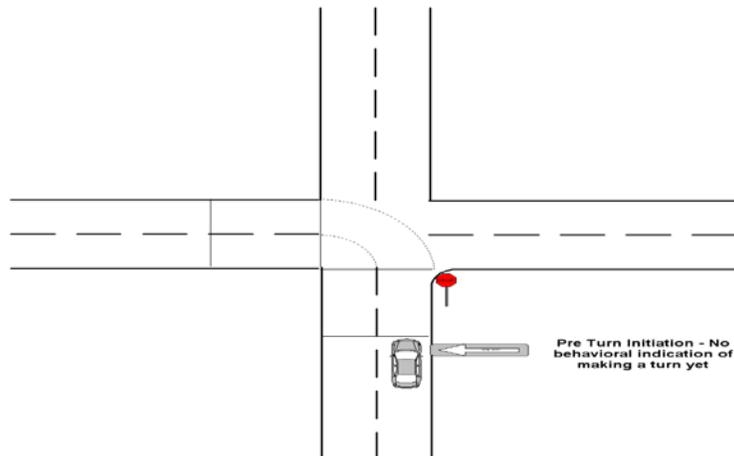


Figure 7. Illustration. Zone of initiation, with the vehicle positioned in a pre-turn state (prior to beginning the turn).

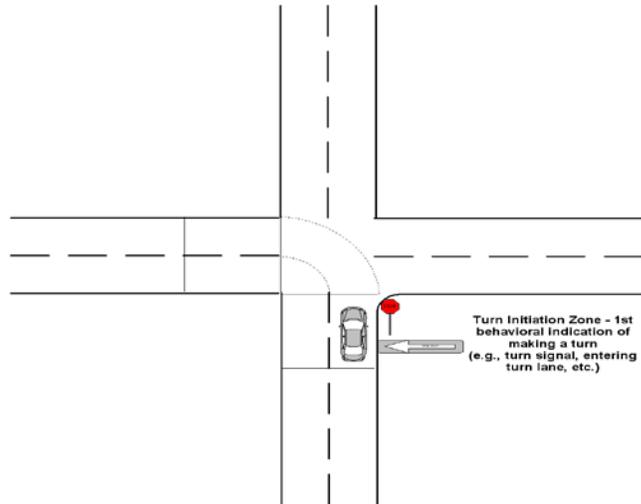


Figure 8. Illustration. Zone of initiation, where the vehicle has just begun the turn.

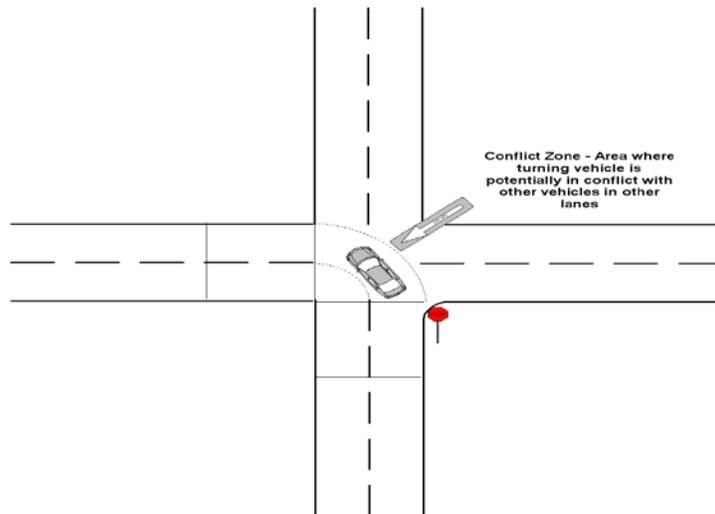


Figure 9. Illustration. Zone of conflict. The driver is actively steering the vehicle through the turn and is in an area of the intersection where conflict with other vehicles is possible.

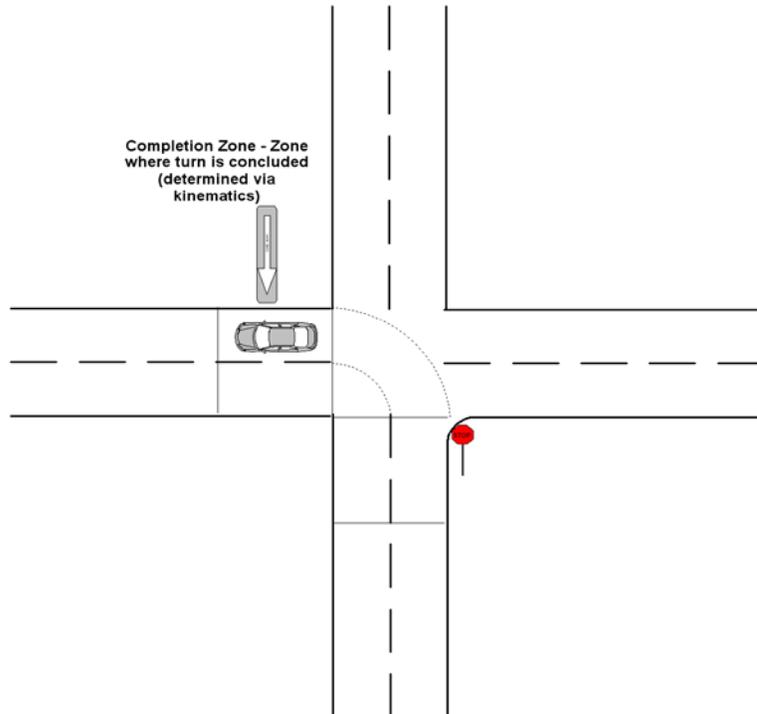


Figure 10. Illustration. Zone of completion. The driver has completed the turn and is stabilizing the vehicle in the new lane of travel.

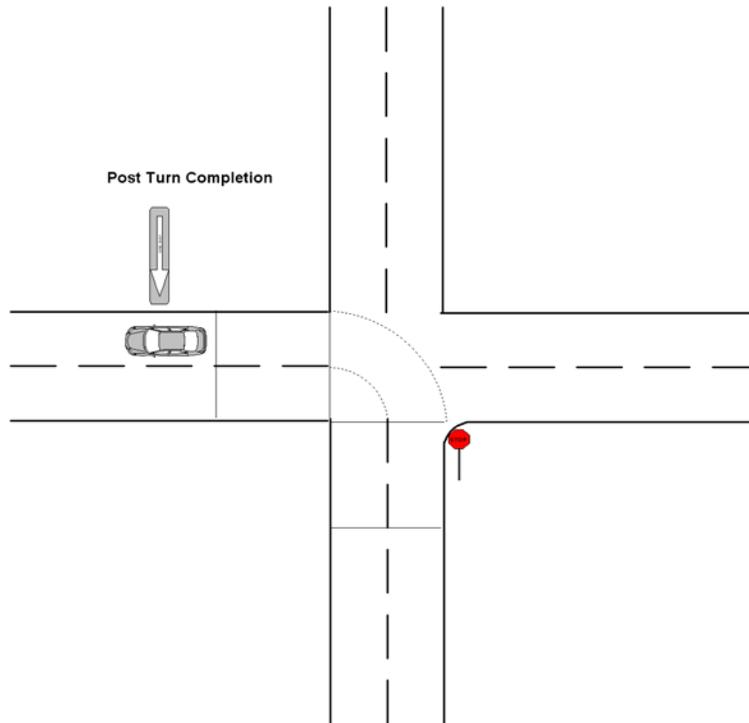


Figure 11. Illustration. Vehicle in the post-turn state, just past the zone of completion.

Participant Sample

A sample of 36 drivers was identified, 12 in each of three age groups. Four drivers in each age group made at least one left turn at each of three intersections that were selected for study. None of the parents or teens were familially related to each other. Thus, there were 4 drivers from each age group contributing data to the design, for each of three intersections (12 drivers altogether).¹ This sample of data formed the basis for the analyses reported for Phase 1 results. (It is worth noting that finding a matched sample of drivers for a set of matched left turns at matched intersections within the larger pooled naturalistic data set proved nontrivial. It was surprising to find that even within so much naturalistic data only a small matched sample could be found.)

RESULTS AND DISCUSSION OF ANALYSES

Analyses for Phase I were done using SPSS statistical analysis software.

¹ Power to detect age group differences was quite low in this design, but was constrained by the amount of data available from the naturalistic data sets. It will take even larger naturalistic databases to strengthen this power in future extensions of this work. Power to detect differences across all drivers was adequate. It is just age group effects that often did not reach significance, but which may be present (if more observations are available).

Visual Scanning Results

Proportion of Glances

The dependent measure of proportion of glances was analyzed using a mixed design, with two between-subjects variables: Intersection Turn Path (104, 201, 302) and Age Group (younger, middle, older). One within-subject variable was used: Zone of Turn (initiation and conflict).

The proportion of glances to the forward area was significantly affected by the independent variable Zone of Turn, $F(2, 50) = 12.66, p < .0001$. As shown in Figure 11, drivers made a significantly higher proportion of glances to the forward path when they were in the zone of conflict. This is sensible, since it is necessary for a driver to look at the future heading of a vehicle's path in order to steer the vehicle

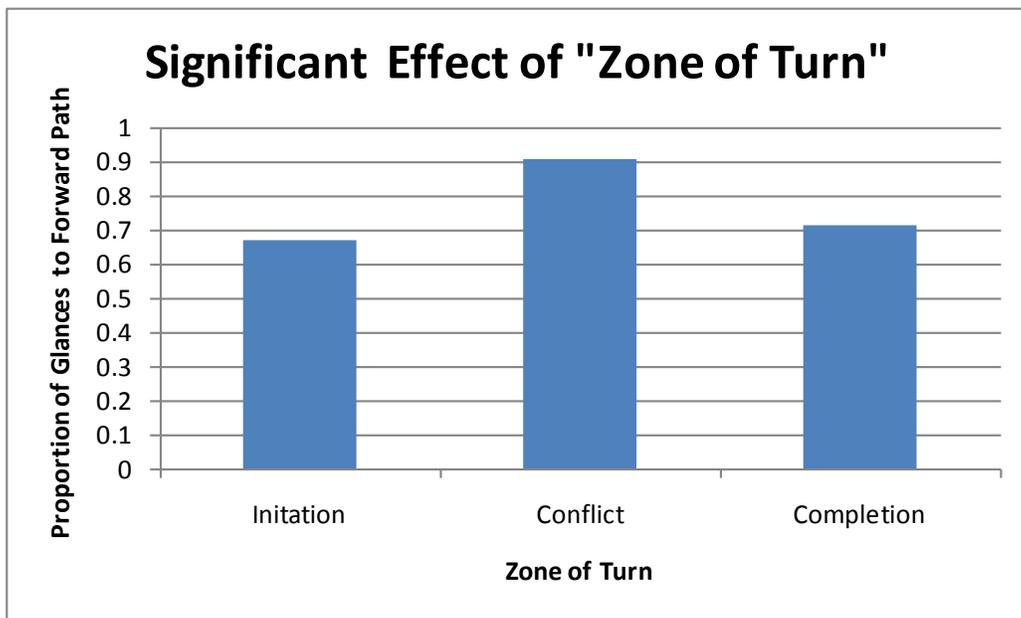


Figure 12. Chart. Effects of Zone of Turn on proportion of glances forward.

The proportion of glances forward was also significantly affected by Intersection Type, $F(2, 25) = 6.24, p < .0001$ (Figure 12). Driver glances to the forward path were significantly higher for the second type of unsignalized intersection than for the other types of intersections. This is the type of intersection that had oncoming traffic moving through the intersection toward the left-turning driver's vehicle, under circumstances in which there were no traffic lights to protect the turn, only a stop sign for the driver. This may indicate that drivers in all age groups were sensitive to the need for increased attentiveness in visually inspecting this oncoming stream of traffic in order to select a gap large enough to turn left.

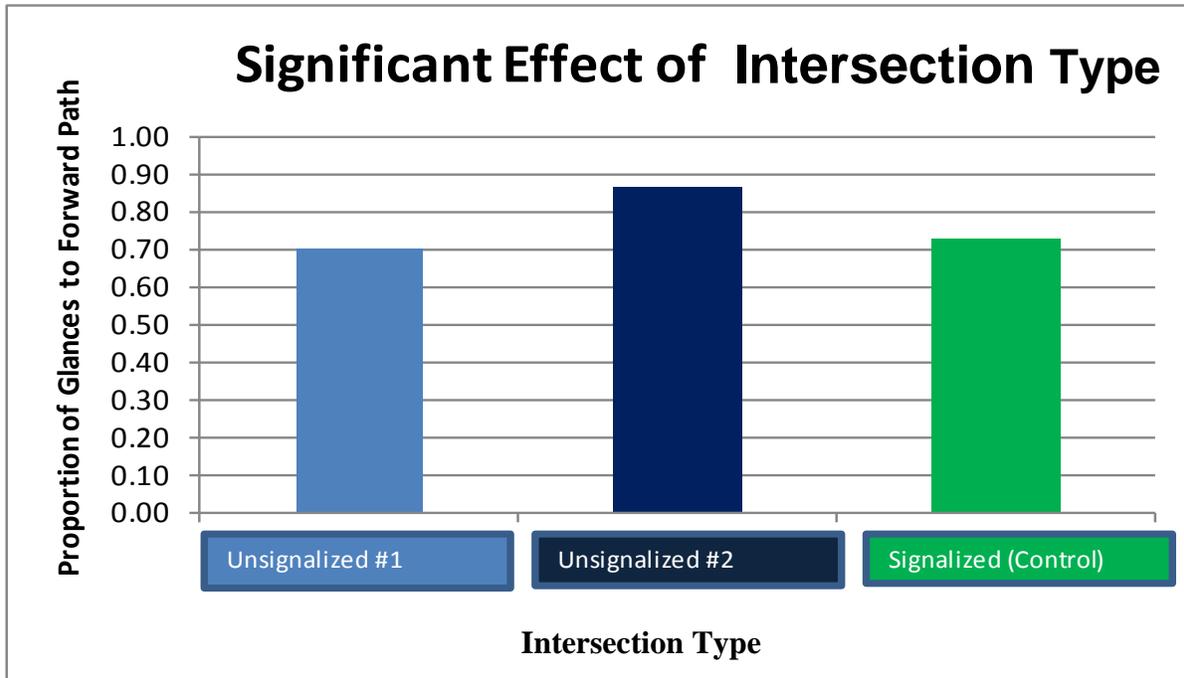


Figure 13. Chart. Effects of Intersection Type on proportion of glances forward.

In addition, there were several significant interactions. One of these was a significant interaction of Intersection Type \times Zone, $F(4, 50) = 3.36, p < .016$. Shown in Figure 13, this interaction revealed that the proportion of glances to the forward area was affected differentially depending upon the type of intersection. In particular, the proportion of glances to the forward area was notably higher for both the zone of initiation and the zone of conflict for the type of unsignalized intersection that had oncoming traffic moving through the intersection toward the left-turning driver's vehicle under circumstances in which there were no traffic lights to protect the turn, only a stop sign for the driver. For the other intersection types, this elevation in the proportion of forward-looking glances occurred primarily in the zone of conflict. In the zone of completion, the proportion of forward-looking glances was similar across all intersection types.

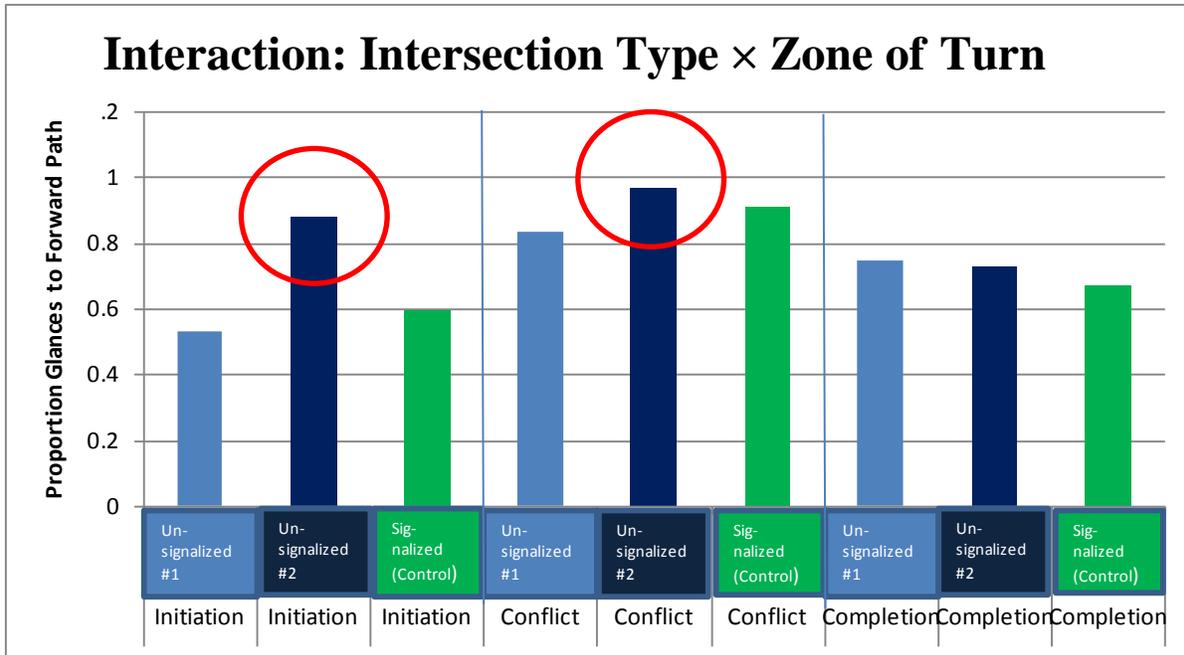


Figure 14. Chart. The interaction of Intersection Type × Zone of Turn on proportion of glances forward.

In addition, the data are broken out by Age Group in Figure 14 and Figure 15 for reader interest.

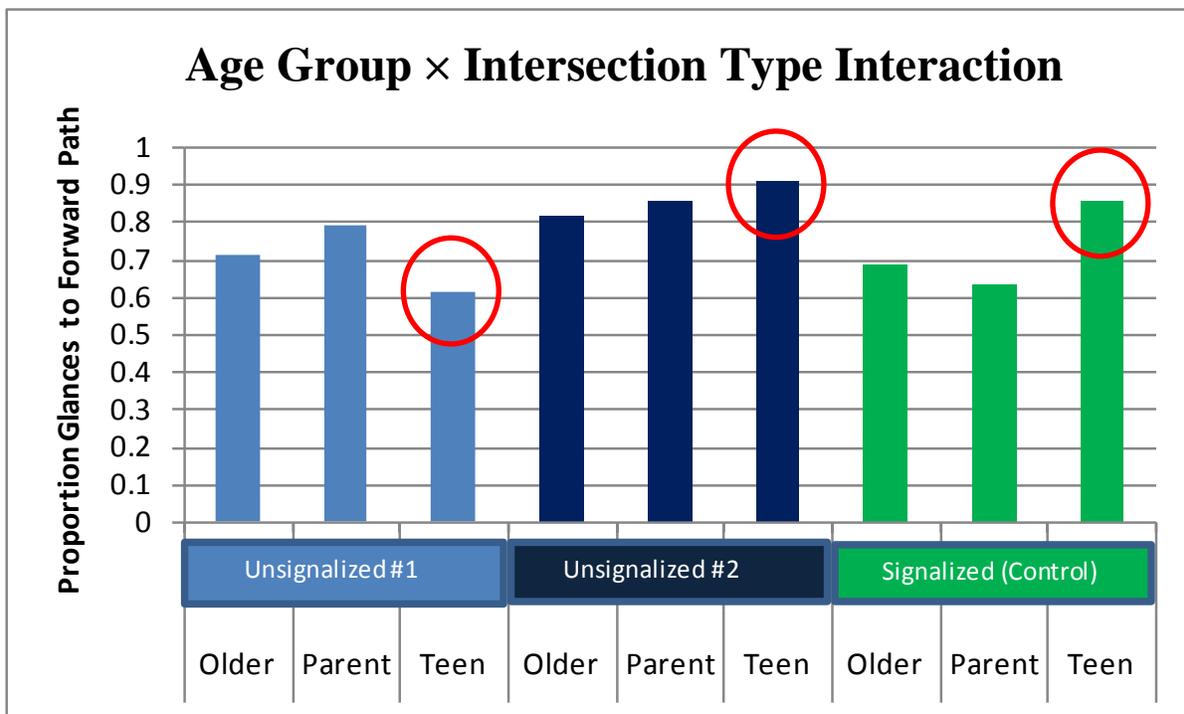


Figure 15. Chart. Data broken out by Age Group and Intersection Type.

When the data are plotted by Age Group \times Intersection Type, it can be seen that teen drivers show slight differences from the parent and older drivers in the proportion of glances forward in all three intersection types. In contrast, older drivers and parent drivers showed similar patterns of forward glances across all three intersection types (proportions that were not statistically different from one another). However, in Figure 15 this pattern is further broken out by Zone of Turn. It shows that the differences between age groups was most pronounced for the zones of conflict and completion. Particularly in the signalized intersection, when drivers were in the zone of completion, there was a higher proportion of rearward glances (see Figure 15). These glances may have been made to confirm that the driver's entry into an accepted gap within the stream of traffic was successful (and had not left too small a gap to the vehicle behind them after they made the turn). However, only older and parent drivers showed an increased proportion of glances rearward in the zone of completion for the signalized intersection. Teens made a much smaller proportion of glances rearward in this zone for this intersection type (see Figure 16).

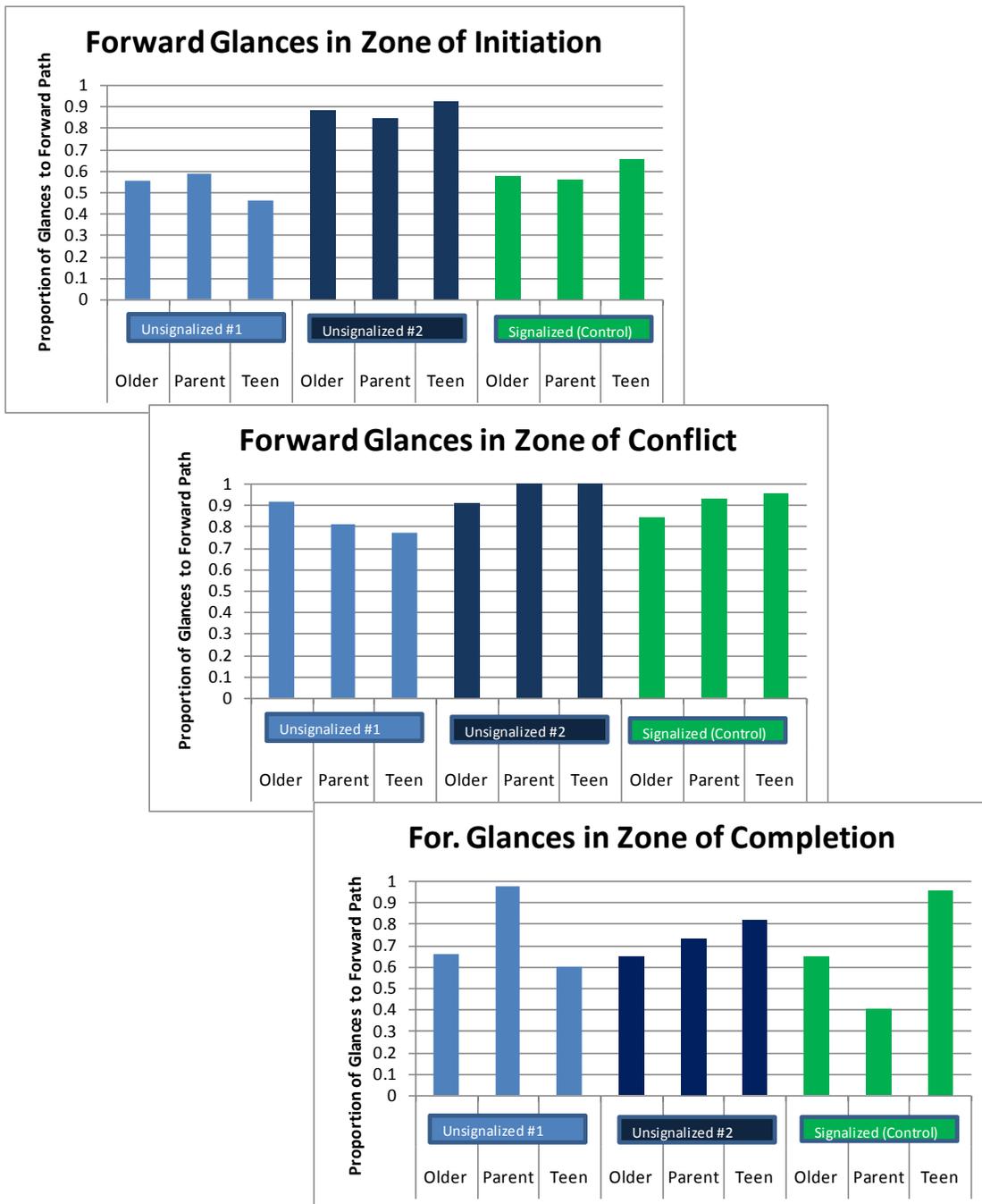


Figure 16. Chart. Data plotted by Age Group × Intersection Type × Zone of Turn.

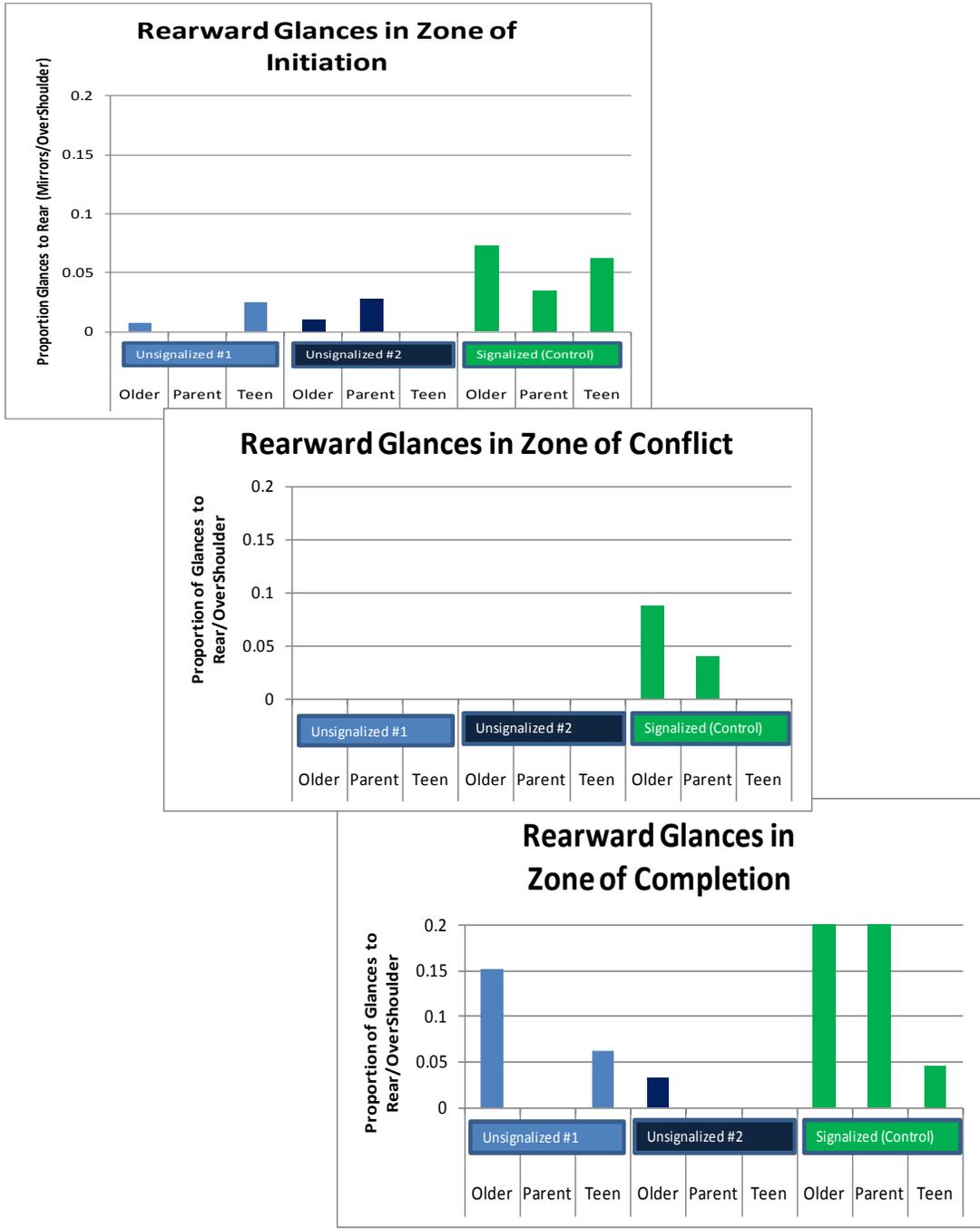
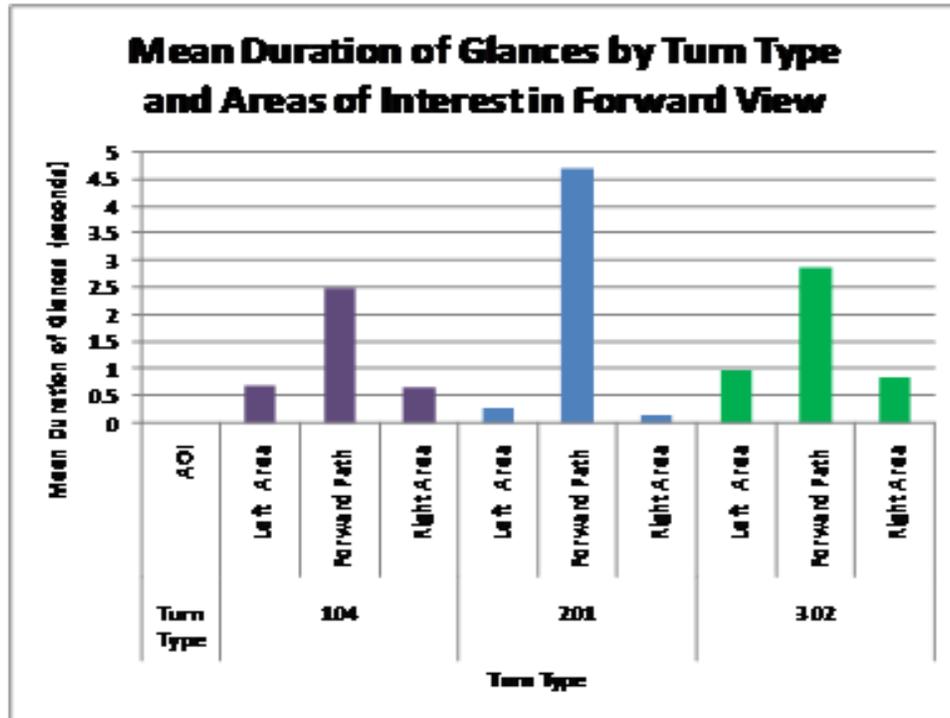


Figure 17. Chart. Rearward glances as affected by interaction of Intersection Type, Turn Zone, and Age Group.

Mean Glance Duration

Analyses of the duration of individual glances made during turns revealed some interesting patterns. There was a main effect of Zone of Turn (only two levels were examined in this analysis, the zone of initiation and the zone of conflict), $F(1, 26) = 14.55, p < .001$. Mean glance durations were longer during the zone of initiation than during the zone of conflict. This finding contrasts with the analysis of proportion of glances (reported in the prior section), where the highest proportion of glances occurred during the zone of conflict. In the mean glance duration analysis the longest duration glances occurred during the zone of initiation. These two metrics provide different information about visual processing. Glance duration is associated with the amount and complexity of information extraction from an area that is being fixated. Proportion of glances is indicative of the amount of active scanning, or information gathering from different points within a zone. Thus, during the zone of initiation, it would appear that drivers are extracting more information within each glance. During the zone of conflict, they are perhaps more actively sampling different points within the region of focus.

For mean glance duration, there was also a main effect of Area of Glance, $F(2, 52) = 59.86, p < .001$. Mean glance durations were longer to the forward path than for other areas (to the right or left of path). This was especially true for the 201 Turn Type, as can be seen in Figure 17 and as confirmed by a significant interaction between Area of Glance and Turn Type, $F(4, 52) = 5.65, p < .001$. This 201 Turn Type also led to the shortest durations for left and right glances. Interestingly, this pattern (of lengthened glance durations to the forward path) was most pronounced for the 201 Turn Type, which is the one that had oncoming traffic moving through the intersection toward the left-turning driver's vehicle under circumstances in which there were no traffic lights to protect the turn, only a stop sign for the driver. It is for this intersection that drivers had to determine a gap size through which to turn left, and thus would have had the highest visual information-extraction demands among the intersection types.



104 = Unsignalized/unprotected intersection with no signal/signage, no through traffic
 201 = Unsignalized/unprotected intersection with stop sign
 302 = Signalized/protected intersection – control

Figure 18. Chart. Effects of Turn Type and Area of Interest (glance location) on glance duration.

Although there was no significant main effect of Age Group, nor any interactions with Age Group for this variable, the mean glance durations are shown in terms of Age Groups in Figure 18. As can be seen, the means for middle-aged parent drivers and the older drivers (blue and green bars) are very similar, with the longest glances to the forward area. Teens also showed this same tendency (purple bars), though with slightly shorter (but not significantly different) glance durations to the forward path.

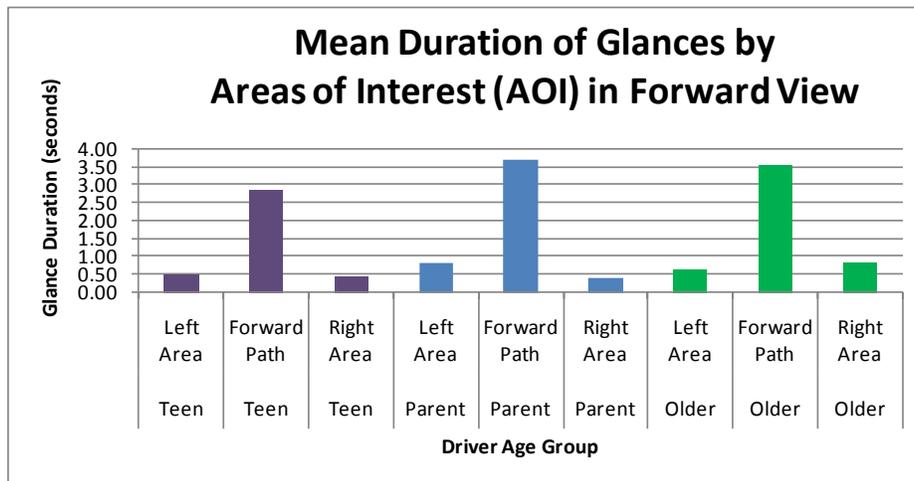


Figure 19. Chart. Effect of Areas of Interest and Age Group on glance duration.

Head-Turning Behavior

One of the key insights from Bao and Boyle (2007, 2009) was that the spatial extent of visual scanning is of key interest. However, new methods were needed for quantifying and analyzing differences in the spatial extent of scanning within naturalistic data during turns at intersections, both in terms of head turns and in terms of eye movements.

Therefore, this research developed techniques to:

- Evaluate head turning using automated techniques (in a preliminary way). These were based on the use of the MASK, a capability developed by VTTI for monitoring head position during driving.
- Compare analyses of the extent of head turning to neck-flexibility assessments from prior data (for older drivers).
- Develop techniques for analyzing the spatial distribution of scanning (eye glances not head turns) and compare them to head-turning assessments.

The dependent variable Range of Y-Average Rotation was first analyzed using ANOVA (in SAS JMP). Subsequently, the findings were visualized for purposes of illustration. The ANOVA revealed that there was a significant main effect of Zone of Turn $F(2, 19) = 35.13, p < .0001$, on head turning, as well as a significant three-way interaction of Zone of Turn \times Age Group \times Intersection Type, $F(4, 19) = 3.40, p < .0295$. Since the main effect was modified by an interaction with Age Group and Intersection Type, the description below focuses on the interaction.

The results for this three-way interaction are depicted in Figure 20. As can be seen, the behavior of older drivers is distinctly different for Intersection 104 (the unprotected turn) than for Intersection 302 (the protected turn, shown to the right of the dark line). For Intersection 104, the older drivers exhibited much narrower ranges of head rotation in the zone of initiation—or beginning zone of the turn—than for Intersection 302. Intersection 104 is the intersection that is unsignalized with no signal and no signage, and thus leaves the turn completely unprotected but has no oncoming through traffic (the driver must merge into a gap in the traffic coming from the right). Thus, the largest visual load is in the traffic stream to the right, which is also the direction from which the driver’s vehicle would be struck if an error in judgment is made. Teens showed the opposite pattern from older drivers (namely, using a wider range of head rotation in the zone of initiation for Intersection 104 than for Intersection 302).

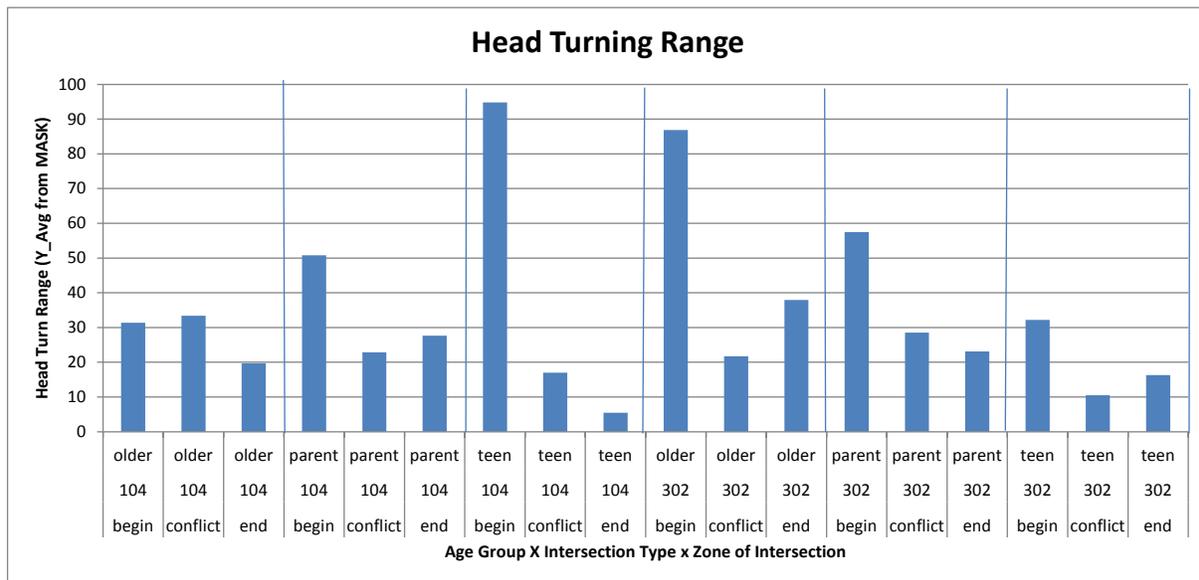


Figure 20. Chart. Interaction of Age Group × Intersection Type × Zone of Turn on head turning as assessed by MASK (range of Y_Avg).

Following the statistical analysis of the MASK values for head turning, an illustration was created to show not only the breadth of head turning for each age group within the zone of turn initiation for Intersection 104 but also the spatial orientation of the head within a 180-degree space (90-degrees is ahead/up). This is shown in Figure 21. As can be seen, the preliminary findings were striking and show that not only did the older drivers exhibit a narrower extent of head turning, but their heads were turned more toward the stream of traffic into which they were turning than were the heads of drivers in the other age groups. With the vehicle in this position (at the beginning of the turn), the glances of the drivers may still likely have been scored as “forward through the windshield,” as indeed the analyses of glance proportion and duration suggest, given that the highest values were for the forward area. Thus, the head turn data carry new and important information about something that the age groups are doing differently.

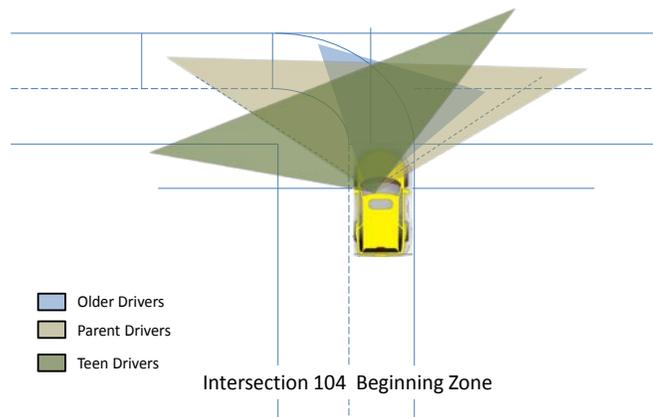


Figure 21. Diagram. Depiction of “spatial range” of head turning for each age group.

Neck Flexibility Assessments

Since aging tends to bring some loss in neck flexibility, it was of interest to explore the extent to which such losses might explain the narrowed range of head turning that was observed for older drivers in the MASK data. This was possible to do because neck flexibility was measured in the original Older Driver study. The results for older drivers revealed that the average neck rotation for older drivers (136 degrees) was less than the norms reported in the literature for active young adults (ranging from 155 degrees for men to 162 degrees for women) and conformed to a loss of about 4 degrees of flexibility per decade of age reported to typify aging in a meta-analysis of neck flexibility across lifespan (Chen et al., 1999). This is illustrated on a coordinate system shown in Figure 22, which shows the range for older adults in orange heavy lines and the range for younger adults in blue heavy lines.

However, while the older drivers in this research had about 26 fewer degrees of neck flexibility than the norms for younger active adults, and while limited neck flexibility is consistent with a pattern of less head rotation that is seen in the narrower ranges of head rotation extracted from the MASK data (depicted in Figures 20 and 21), this loss of range still cannot fully account for the large extent of narrowing in head turning that was measured by the MASK for older drivers within Intersection 104. Older drivers used only 30 degrees of head rotation during Intersection 104 (out of the 136 degrees of flexibility of which they were capable). It would thus appear that the narrowing of head rotation during the Intersection 104 turn is functional in nature, that is, reflects an attentional strategy that the older drivers were using, rather than a physical limitation due to aging. It would appear that older drivers had their heads turned slightly more toward the side of the vehicle from which the stream of traffic into which they had to merge was coming, and it is this traffic that would most likely strike them if they made an error of judgment.

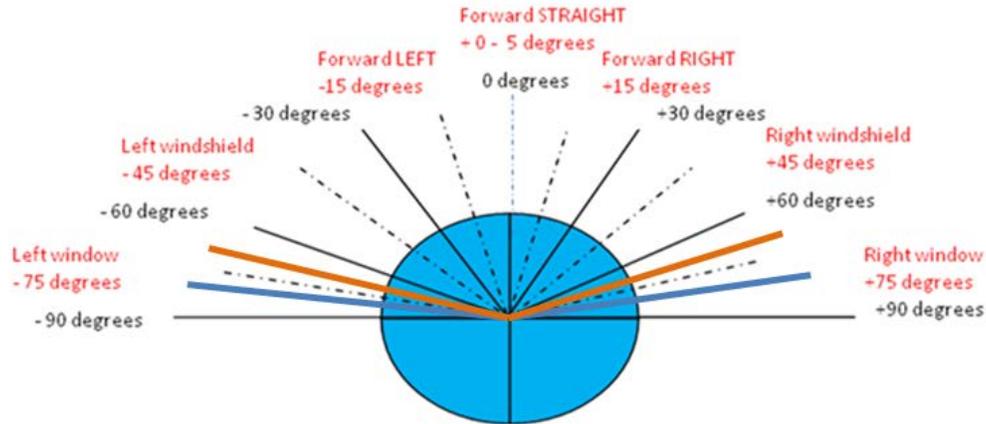


Figure 22. Illustration. Approximate range of neck flexibility for active young adults (heavy blue line) vs. older adults in this research (heavy orange line).

It is also worth some further reflection to consider these results for head turning in the context of the results for glance proportion for older drivers in Turn Type 104 for the beginning segment of the turn (circled in red in Figure 23). The glance proportions suggest that the preponderance of glances are to the forward area, which seems, on the surface, to be somewhat inconsistent with the results for head turning (which show head position to be oriented slightly rightward). Similarly, Figure 24 shows that the mean glance durations were also longest to the forward view. This tells us that the human analysts who scored the video of glances judged the glances during the beginning of the turn to be mostly forward through the windshield (nearly 60%) even though the head was turned slightly toward the right (based on data from the MASK). However, according to glance-scoring guidelines, a glance is attributed to the “forward” area if it occurs in the area between -45 and $+45$ degrees, and is attributed to the “right windshield” location only when it occurs between approximately 45 and 60 degrees rightward of line-of-sight straight forward from the driver (considered 0 degrees), as shown in Figure 22. For the most part, the cone of head turning for older drivers fell between -15 degrees and $+45$ degrees. Thus, while the head was positioned slightly rightward (and attention directed perhaps toward the traffic stream coming from the left of the driver, the traffic stream into which the driver was turning), the head was not turned over 45 degrees rightward, so the direction of gaze would still have fallen within the area defined by glance-scoring criteria as “forward.” Thus, the data from glance-scoring and head turning were consistent with each other. Yet the head-turning data from the MASK revealed new insights not apparent from the glance data about a slight shift of attention toward the right by older drivers and the likely nature of information being attended to and processed by older drivers in the beginning zone of the unprotected left turn at the T-intersection. This is the direction from which traffic is coming and into which the driver must merge when turning left. It is the area in which the driver must estimate the size of a gap in traffic and choose an appropriately sized gap through which to initiate the turn. It is one of the scenarios where the driver is vulnerable to being struck if an error is made.

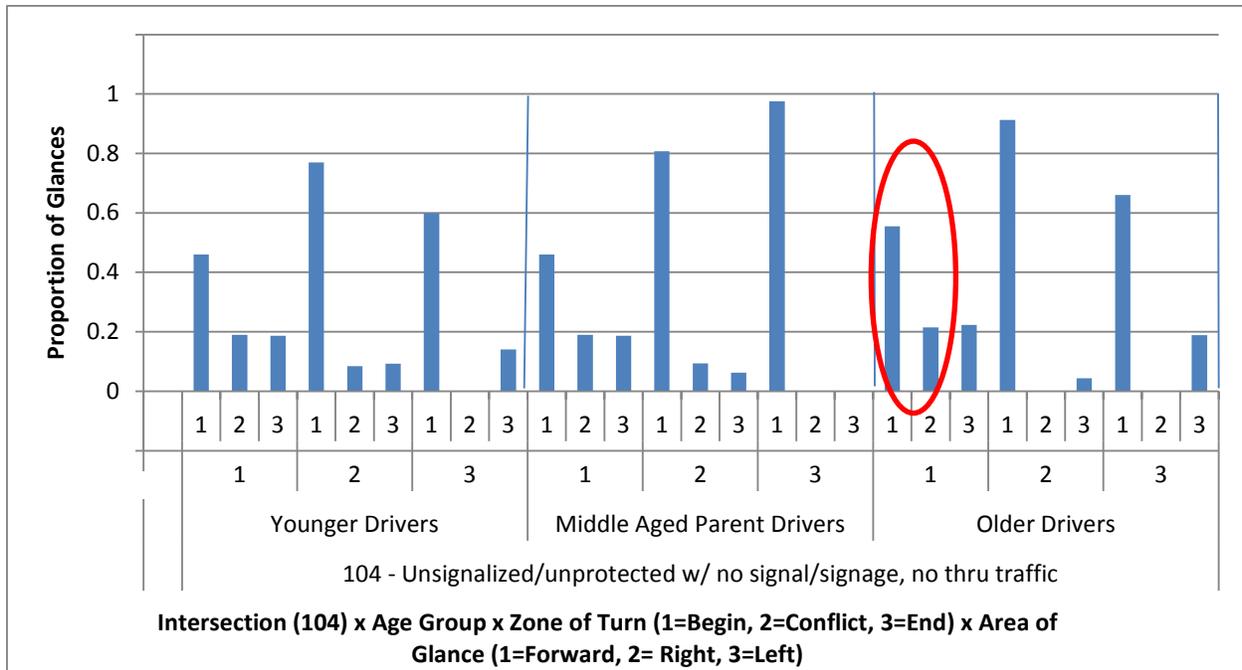


Figure 23. Chart. Data for proportion of glances.

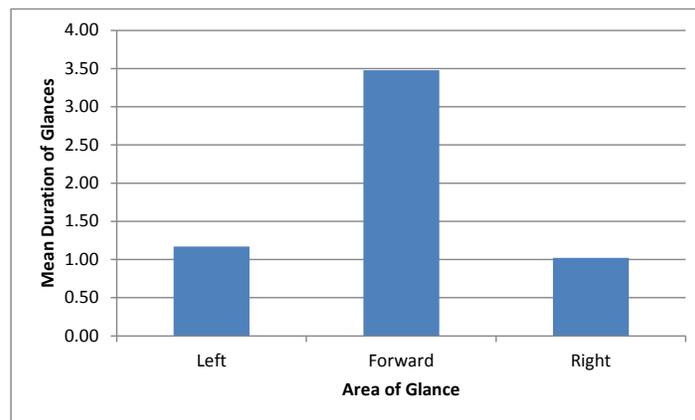


Figure 24. Chart. Data for mean duration of glances.

Spatial Distribution of Glance

Prior to discovering that the data from head turning augment the findings from glance data rather than duplicate them, the project developed a technique for creating a visualization of the spatial distribution of eye glances over an epoch of time (such as during a zone within an intersection). This was done with the hope that head turns and eye glances could be examined in a common format. This technique was intended to depict the duration and range of locations over which gazes were distributed during each segment of the left turn (for each age group). An example is illustrated in Figure 25.

The resulting plot shows a concentration of glance time toward the “forward path” (toward oncoming traffic through which a gap must be chosen). Within this plot, each concentric circle indicates the percentage or proportion of visual glance by location.

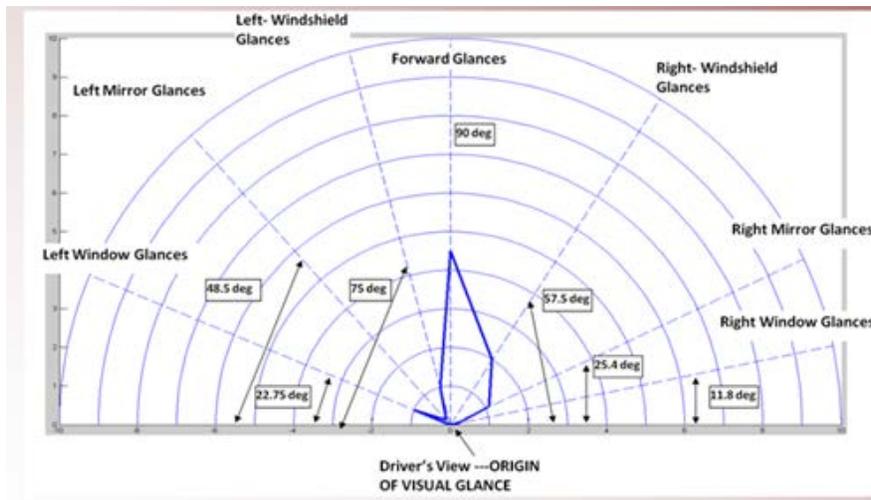


Figure 25. Illustration. Spatial distribution of Glance Locations × Durations.

While the spatial plot shows a preponderance of glance allocations to the forward direction, it also shows some dispersion to the rightward side, somewhat similar to the cone of head turn generated by the MASK (albeit differently shaped).

The sample summary data used to generate the illustrative plot above are shown in Table 6. The data that were used are illustrative only, but are within a range that is representative of the actual means that are depicted in Figure 24. This technique could, of course, be used to depict data from any series of epochs (a trip, or an intersection event, other events).

Table 8. Sample summary data used in spatial glance distribution technique.

Glance Location	Glance Percentage by Duration
Left Window	10%
Left Mirror	1.6%
Left Windshield	10.06%
Left Windshield	10.06%
Forward	45%
Right Windshield	20%
Right Mirror	11%
Right Window	2.34%
TOTAL	100%

The angular measures for each location are located relative to the driver’s straight-ahead line-of-sight position in the car (shown in this plot at 90 degrees). It can be seen that the left-windshield

location is closer to the forward location in comparison to the right windshield, as the driver has a larger area to scan on the right. This is similar for right window and right mirror in comparison to the left areas. During glance coding of video data, 20 codes are typically used, but only those listed in Table 6 were used to construct this figure.

Plots of this type were not generated for the actual data from this study given the insights that were gleaned from the MASK data itself. However, the technique is set forth in the event that it proves useful to others in future research.

Driving Behavior (Kinematic) Variables

There were significant effects of age on driving behavior at intersections, as evidenced by analysis of speed and other kinematic measures.

Speed Through Intersections

There was a significant effect of Age Group on the speed at which drivers negotiated the intersections, with older drivers proceeding significantly more slowly. Overall, the slowest speeds were observed at the intersection that was unprotected and had no signal or sign, and no through traffic, perhaps indicating that all drivers were most cautious at this type of intersection. Details on this analysis are provided below.

Age groups differed significantly in the speed with which they drove through intersections (all age groups differed significantly). Older drivers moved through the intersection turns at slower speed, especially when the intersection was unsignalized. This slowing was exhibited even when a stop sign was present to assist. Teens drove more rapidly through turns than others; speed through the intersection with a stop sign was similar to the protected intersection. This is shown in Figure 26 below.

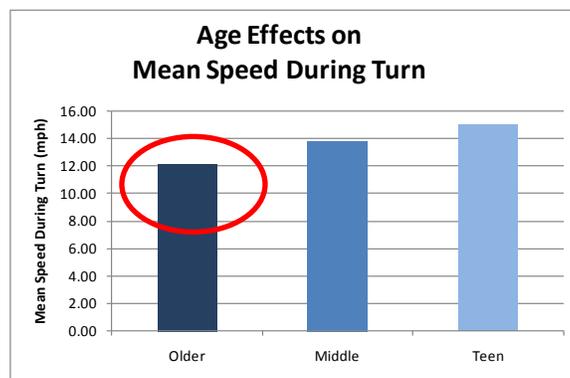


Figure 26. Chart. Age Group effects on mean speed during turn.

Furthermore, there was a significant interaction of Age Group and Intersection Type, in which middle-aged drivers exhibited a different turn speed for each type of intersection. This is shown in Figure 27. However, teen drivers treated the intersection with a stop sign as if it were similar to a signalized intersection. Older drivers treated that intersection more cautiously, as if it were

completely unsignalized and unprotected (exhibiting speeds similar to the intersection without any signal or signage).

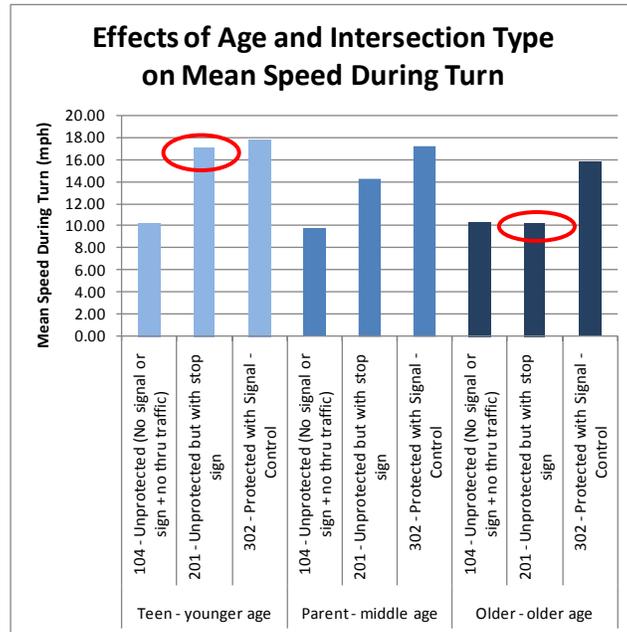


Figure 27. Chart. Interaction of Age Group and Intersection Type on mean speed.

SUMMARY AND CONCLUSIONS FROM PHASE 1

Phase 1 of the research yielded several interesting findings about driver behavior through intersections. These included the following key results:

- Visual processing patterns were uniquely affected by turn-specific variables. Behavior during unprotected turns differed from that during the comparison, protected turn. In addition, the two types of unprotected turns also differed from each other.
- Scan patterns were affected by the changing information needs and demands as a driver progresses through the different zones of a turn:
 - The visual processing requirements within each zone of the turn appear to be unique.
 - During the zone of initiation, one of the factors that matters is whether or not there is a stream of oncoming traffic, and whether there is any control signal or signage to assist the driver with passing through it. These factors affect glances made by drivers as they prepare to turn. Glance durations lengthen with the need to extract information (e.g., when there is no control but there is oncoming traffic, gap estimation must be performed and driver glances lengthen as they try to estimate and select a gap through which they can safely turn.)

- During the zone of conflict, there is a need to both look at the path along which the vehicle is being steered (the turn path), while at the same time some need to ensure that threats to safety are not present. This affects the locations to which glances are directed. If there was no oncoming traffic, it appears that glances were directed to areas of perceived threat, at least for older drivers making left turns in the T-intersection with stop-sign-only control.
- During the zone of completion, there is a need to look at the new forward path of travel and possibly an increased need to check the rearward view to be sure that the turn was completed without creating an undue threat from a vehicle closing rapidly from the rear.
- There were suggestions of age group effects and differences. Some were statistically significant and some were not (but the power to detect differences between age groups was limited by power, since this variable was represented by the fewest observations in the experimental design).
 - Age effects on glance patterns were not strong, but there were some subtle suggestions of differences in some conditions. Visual scanning differences by age did not appear to be as simple as studying one intersection and one turn type, and then generalizing findings across age. Rather, visual processing appeared to be affected by specific factors that are unique to different types of intersections (such as the presence or absence of signals protecting turns; the geometry of the intersection, whether a three-way T-intersection with no oncoming traffic stream or a four-way with an oncoming traffic stream; and perhaps other factors).
 - However, there were definitive age group effects on head turning. This replicates some of the key findings from Bao & Boyle (2007, 2009). These results suggested that older drivers scanned more narrowly and strategically oriented their scans in the direction of greatest threat for certain types of unprotected left turns (as compared to middle-aged and younger drivers, who scanned more broadly and oriented their heads differently during information gathering at turns of certain types). Further, these head-turning results provided insight into why the results from glance analysis were more subtle than definitive—specifically, because the orientation of head positions were only slightly turned, leaving the direction of eye gaze within the spatial area defined as forward by glance-coding criteria. Thus, eye-glance criteria would not have revealed the subtle differences in attentional allocation unless head turning had been analyzed as well.
 - There were also age group effects in driving behavior, with older drivers proceeding through turns at slower speeds, especially when an intersection was unsignalized.

NEXT STEPS

These results led to several questions and suggested that an in-depth focus on one intersection may be beneficial in order to explore some specific issues:

- Visual Scanning – Can the breadth of scanning during turns be quantified for different age groups and, if so, are there differences between age groups? Do they substantiate the strategic differences in visual-information gathering between age groups that Phase 1 seemed to reveal?
- Driving Behavior – Can a deeper examination of driving behavior through the intersection provide a more complete picture of the factors that affect visual scanning (such as gap acceptance)? This would involve analyzing:
 - Approach speeds to intersections
 - Turn initiation speeds
 - Times through intersection
 - Gap acceptance and rejection
- Key factors related to the intersection itself – Can an examination of key traffic, roadway, or other factors that may affect visual scanning or behavior reveal any influences of relevance? Another factor which could not be directly determined within the current dataset was the degree of familiarity each participant had with each of the intersections where behaviors were measured. This could have an impact on glance patterns as well as the relative degree of safety associated with each intersection crossing.

These issues formed the basis for Phase 2 of the research and defined the next steps to be taken.

CHAPTER 4. PHASE 2

Phase 2 of the research was conducted as part of a master's thesis project (Aich, 2011) at Virginia Tech (under sponsorship of the project). The summary provided here draws heavily from that thesis. All figures are drawn directly from the thesis (Aich, 2011). The thesis focused in-depth on turns at one particular intersection (the "104" intersection studied in Phase 1) but examined both left turns and right turns. It should be noted that this single type of unprotected intersection explored in this Phase 2 research is one that has emerged as particularly hazardous in recent crash analyses sponsored by the U.S. Department of Transportation (Stutts, Martell, and Staplin, 2009): a T-intersection with only a stop sign, which is depicted in Figure 28. Panel (a) shows the left turn of interest, and Panel (b) shows the right turn of interest. The figure makes clear that while making a left turn, drivers were concerned with traffic streams from both the left (A direction) and the right (B direction), which required drivers to scan the road in two opposite directions in order to find a suitable gap through which to turn. However, for the right turn, drivers were concerned only with the traffic flowing in the A direction (in order to find a suitable gap into which to turn).

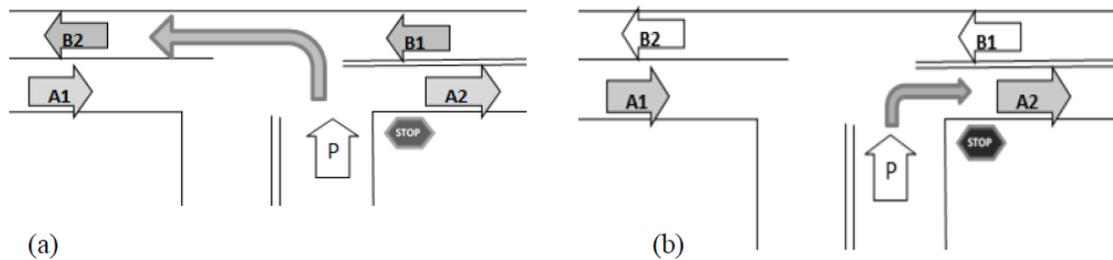


Figure 28. Diagram. Turns of interest in Phase 2: (a) left turn and (b) right turn.

EXPERIMENTAL DESIGN FOR PHASE 2

For the Phase 2 research, the epochs of naturalistic data from matched turns at this intersection were used to populate structured experimental designs in order to perform statistical analyses. These are described in this section, along with the independent and dependent variables upon which they were based.

Two main types of experimental design templates were used, as shown in Table 7. Separate analyses were performed on each dependent variable. Depending upon the particular dependent variable being analyzed, either the two-factor or the single-factor design was used in the analysis.

For each of the various analyses (one for each dependent variable), the participant samples were similar and partially overlapping, but not identical. This is due to the inherent nature of naturalistic data wherein differences arise from the fact that in real driving not all participants made both left and right turns at the same intersection. Therefore, it was not possible to populate fully matched experimental designs between analyses in which all participants appeared in all conditions. Also, in one case, a within-subject variable was added to the two-factor design to enable an analysis of visual scanning effects. This is explained in more detail below.

Table 9. Experimental design matrix templates for two-factor design (left) and single-factor design (right).

Two-Factor Design			Single-Factor Design	
Age Group	Traffic Level	Participant	Age Group	Participant
Young	Traffic present	S_1, \dots, S_n	Young	S_1, \dots, S_n
	No traffic present	S_{n+1}, \dots, S_m		S_{n+1}, \dots, S_m
Middle Age	Traffic present	S_{m+1}, \dots, S_p	Middle Age	S_{m+1}, \dots, S_p
	No traffic present	S_{p+1}, \dots, S_q		S_{p+1}, \dots, S_q
Older	Traffic present	S_{q+1}, \dots, S_r	Older	S_{q+1}, \dots, S_r
	No traffic present	S_{r+1}, \dots, S_t		S_{r+1}, \dots, S_t

It is also important to note that the number of participants varied between each separate design block, so there were unequal numbers of subjects between cells in some instances. Hence, the subject number is denoted in Table 7 with a different letter subscript. Unequal sample sizes require careful treatment during analysis and were handled accordingly.

Independent Variables

Three independent variables were analyzed.

Age (3 levels): *Younger (16–20), Middle-Aged (35–55), Older (70+)*

The younger and older driver groups were again of particular interest. The middle-aged drivers, who were the parents of the teen drivers, served as a baseline comparison for the other driver groups. All familial ties were avoided by either selecting the teen or their respective parent but not both for individual experimental design blocks.

Level of Traffic (2 Levels): *No Traffic, Traffic Present*

The effect of traffic on driver behavior during a turn in a natural driving environment was included to provide a deeper understanding of its effect (e.g., on glance pattern variability and vehicle control). The possibility needed to be examined that the presence or absence of traffic surrounding a driver’s vehicle at the intersection may be a variable that mediates visual scanning and/or vehicle-control decisions.

Glance Location (5 Levels): *Forward Roadway, Left window, Left windshield, Right Windshield, Right Window*

Glance Location was included in analyses as a within-subject variable. Five levels of glance location (rather than three) were included to explore (at a finer level of detail) driver differences in visual scanning during intersection negotiation under varying traffic conditions.

Dependent Variables

Visual Scanning and Visual Behavior

Two measures of the extent of active glancing were examined:

- **Visual Entropy**
Visual entropy was used as a dependent measure of the entire glance distribution (or scan pattern) during a turn. It is a single measure that reflects or characterizes the degree of randomness or extent of spatial dispersion in the distribution of glances, with high values of entropy reflecting a greater spatial extent or variability in scanning as discussed in an earlier section. The method used for calculating visual entropy is provided in Appendix A. As described in Chapter 1, the literature has indicated that there are some significant differences in visual scanning between different age groups (e.g., Bao and Boyle, 2007, 2009). Further, it has revealed how important visual scanning is during intersection negotiation due to the complex geometry and merging traffic conditions that can occur there. Such conditions require multidirectional visual scanning and processing. Visual entropy is a measure that was applied by Bao and Boyle (2009) to scanning within an experiment conducted on the road, and thus was of interest for application to naturalistic data. It should be noted that, in addition to visual entropy, analyses for other glance-related dependent variables were also conducted (e.g., glance duration and glance proportion).
- **Transition Probabilities Between Areas Looked-At (Link Analysis)**
Link analysis was performed to examine the breadth, organization, and sequencing of the visual scan pattern between driver age groups. It is presented visually, and the method for analysis is described along with the results below.

Gap Time Accepted and Rejected

Two separate dependent measures related to gap perception were used:

- Gap acceptance time
- Gap rejection time

The gap acceptance time chosen by the driver to make an unprotected turn in a busy free-flowing stream of traffic for both the signalized and non-signalized intersections was calculated.

In addition to examining accepted gap times, the length of gaps that drivers rejected as being too short to turn was also measured and used as a dependent variable. Previous literature and existing observational studies have pointed out that gap times differ across age groups and so analyses were done to discover whether these naturalistic data would substantiate and extend that work.

It is important to keep in mind that this research was not an experiment in which gap times of pre-specified length were controlled and presented to each driver. They were, instead, naturally occurring gaps of differing lengths. By using both accepted gap times and rejected gap times, it is possible to obtain a more complete picture of driver preferences for gaps through which to turn.

Driving Behavior (Kinematic) Measures

Four kinematic measures of driving behavior were analyzed, each intended to serve a different purpose:

Peak longitudinal acceleration

Peak longitudinal acceleration was usually achieved in the initiation of the turn from a stop; thus, it was informative primarily about driving behavior in the zone of initiation.

Peak lateral acceleration

Peak lateral acceleration was achieved during the middle section of the turn; thus, it was informative primarily about driving behavior in the zone of conflict (during the time when the driver is actually executing the turn).

Peak speed

Peak speed was achieved by the end of the execution of the turn, as the vehicle completes the turn and returns to steady-state, straight-path driving (in the zone of completion).

Average speed

Average speed reflects speed across all three zones of the turn and thus is the only measure that is reflective of the overall turn maneuver.

A larger set of kinematic measures was examined in this Phase 2 than in Phase 1 in order to gain further insight into the age-related differences found in Phase 1 (where older drivers tended to drive more slowly as they made turns through intersections). There are several possible explanations for this slowing, and it was hoped that by using a more diagnostic set of kinematic measures, a deeper understanding of age-related differences could be developed. For example, slower speeds exhibited by older drivers could arise from a sense of increased caution (due to their own awareness that they may be at increased risk), or could reflect the slowing of physical and cognitive processes that many older individuals experience, which may manifest in slower perceptual responses to traffic, slower selection of gaps through which to turn, and slower initiation and execution of turns. At the other end of the age spectrum, teenagers may exhibit faster speeds through intersections, also for numerous reasons. These could include inexperience and lack of knowledge, as well as other factors such as aggressive driving. These possible age-related differences underscore the importance of examining kinematic measures and putting them in the context of these intersection turn scenarios. Measures like peak lateral acceleration, peak longitudinal acceleration, peak speed, and average speed were already available in the data sets and were used to explore whether any strong differences existed between age groups (or were affected by other independent variables).

Statistical Analyses

Analyses of variance (ANOVAs) for Phase 2 were done using SAS JMP software. Tukey post hoc comparison tests, also known as Tukey's HSD test and Tukey-Kramer tests, were applied to significant main effects. The research analysis was accomplished in two parts, with most analyses replicated for the two turn types, left and right turns. This was done because the subject samples between the two turns were not completely exclusive nor matched, but were partially overlapping. (As this is naturalistic data, some drivers made both left and right turns, while some made only one type of turn.) As a result, Phase 2 of the research can be viewed as a two-part

study with two different turn types in the same intersection. No analysis was done to compare the two turn types. They were treated as two separate maneuvers (left and right turn), which were analyzed separately but happened to be at the same intersection. The following section explains in detail the findings from the analyses of the data.

RESULTS AND DISCUSSION

Visual Scanning

Glance Duration

For the analysis of glance duration, and the particular set of data available for this intersection, the Restricted Maximum Likelihood Method (REML) approach to ANOVA was used because the data constitute an unbalanced mixed design. There was only one significant effect, a main effect of Area of Glance, significant for both left and right turns, $F = 38.77, p < .0001$, for left turns, and $F = 33.67, p < .0001$, for right turns. Post hoc Tukey HSD test results are shown in Figure 29 and Figure 30 (where different letters indicate bars that differ significantly). As with Phase 1, glance durations were longest to the forward location for left turns. For right turns, glance durations were longest to the forward location and to the area through the left window (the traffic stream in which a gap had to be selected into which to turn).

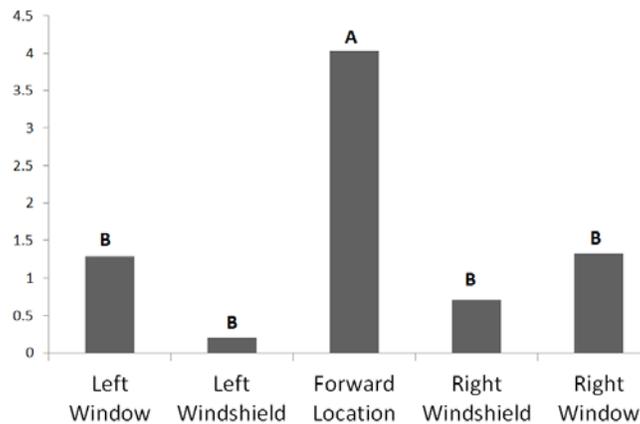


Figure 29. Chart. Mean duration of glances for left turn at the 104 turn type.

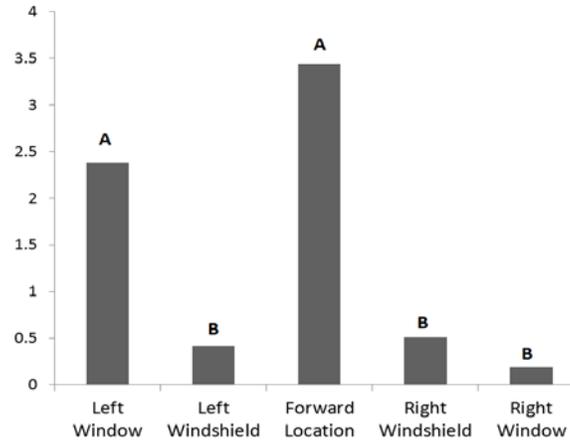


Figure 30. Chart. Mean duration of glances for right turn at the 104 Intersection.

Visual Entropy (Spatial Extent of Scanning)

Left Turns: The analysis revealed that the presence of traffic had a significant main effect on visual entropy, $F(1, 12) = 18.40, p = .0011$. A significant difference between all age groups was found when traffic was present in the intersecting streams of flow while negotiating a left turn, indicating that the presence of traffic prompted a broadening of visual scanning for all age groups.

In addition, the interaction of Age-Group \times Traffic-Level approached significance, $F(2, 12) = 3.05, p = 0.08$. Tukey post hoc comparisons were applied (given that the effect was significant at $p < .10$). These are shown in Figure 30, with significant differences designated by different letters. The largest difference (and a significant one) occurred for the younger drivers, who exhibited the largest increase in visual entropy in the presence of traffic versus when traffic was absent. The effect of traffic on increasing visual entropy occurred for other age groups, but was not quite this large. This increase in visual entropy in the presence of surrounding traffic suggests that drivers scanned more actively and broadly when traffic was present.

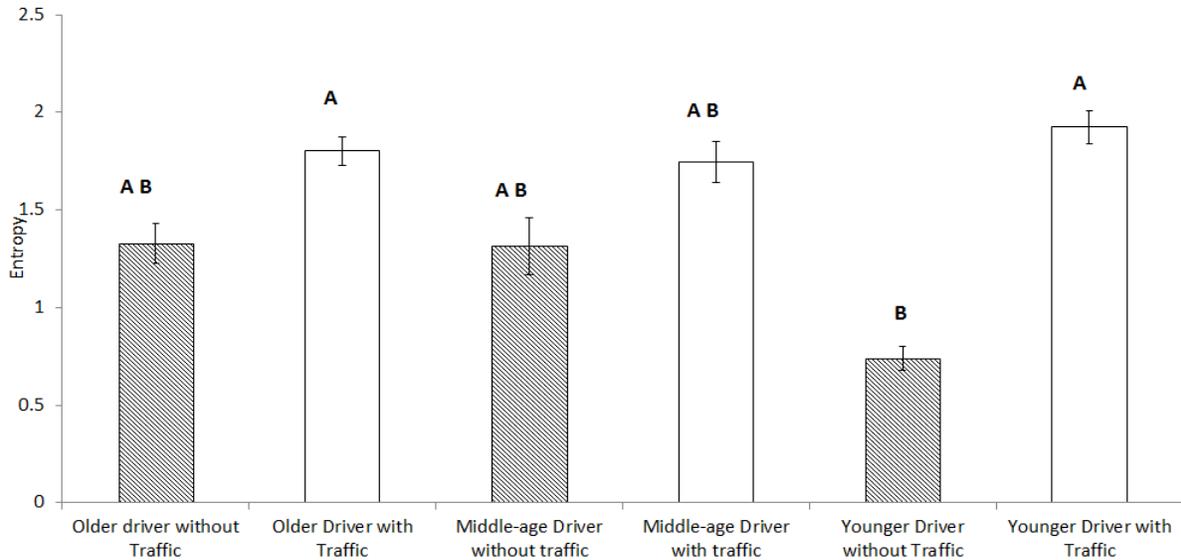


Figure 31. Chart. Entropy means by driver age group as a function of traffic presence at intersection.

Right Turns: The analysis of visual entropy was replicated for the right turn, but no significant differences emerged for either Age Group or Traffic Level.

Distribution of Glances

Aside from visual entropy, the data on proportion of glances by area of interest were used to create some descriptive statistics and illustrations with which to understand visual scanning in more depth. Figure 31 shows the glance distribution across all three age groups while making a left turn. For left turns, most driver groups had a similar distribution of glances by location for this T-intersection, with the forward-looking glances constituting almost half of all glances, followed by glances out through the window areas. The most remarkable difference is for older drivers. The area to which they devoted the second most glances was through the right window followed by the left window. This was the opposite of the pattern for both the middle-aged drivers and younger drivers. More specifically, the older drivers had 10% higher glances to the right window than the left window, which is about 60% more than the glances allocated to the left window. This is consistent with a strategic shift of attention toward the right that was suggested by the head-turn analysis from the MASK in Phase 1 for this intersection. It suggests that older drivers are particularly concerned by the stream of traffic from the right (during the left turn), the traffic stream that could potentially strike their vehicle if they misjudge the gap into which they are turning.

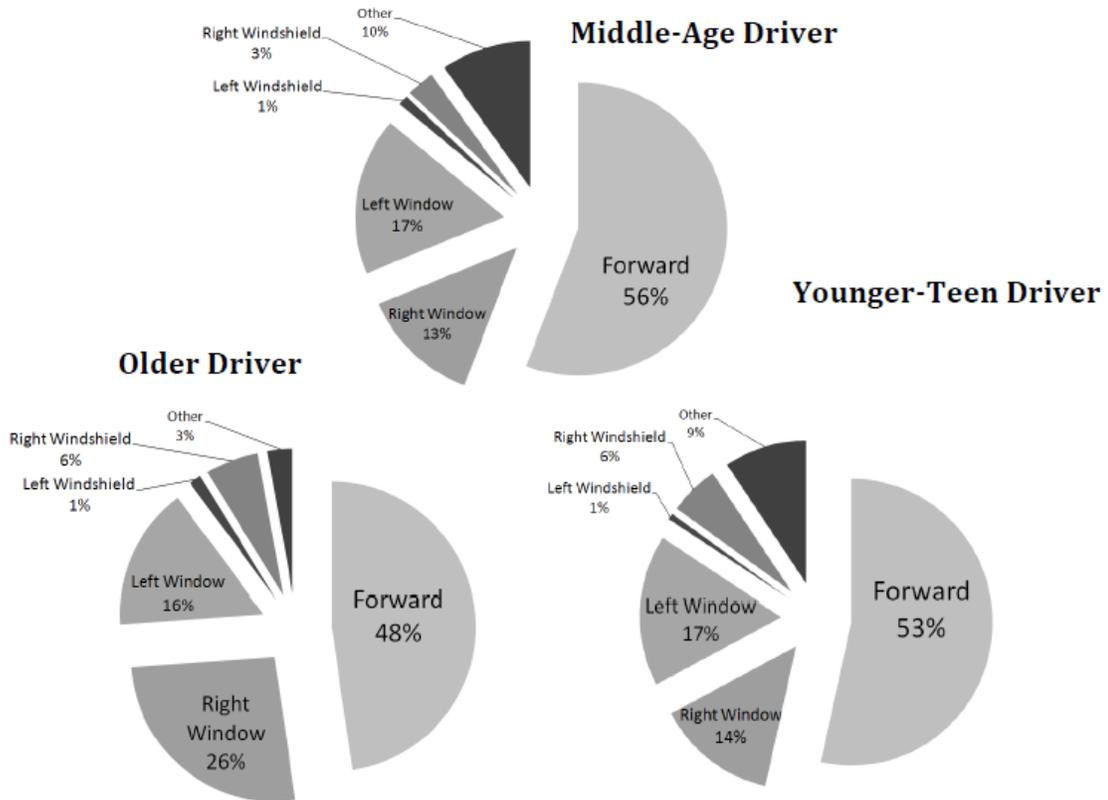


Figure 32. Chart. Distribution of glances for all age groups during left turns.

Similar to the glance distribution for the left turn, there was a pattern within the glance distribution for the right turn as well, with the forward glance location having about 50% of the glances (Figure 32). The pattern was more consistent across age groups for the right turn, with left window glances exhibiting the second highest glance percentage. This, again, suggests that drivers (all drivers in this case, not just older drivers) are particularly concerned by the stream of traffic from the left (during the right turn), the traffic stream that could potentially strike their vehicle if they misjudge the gap into which they are turning.

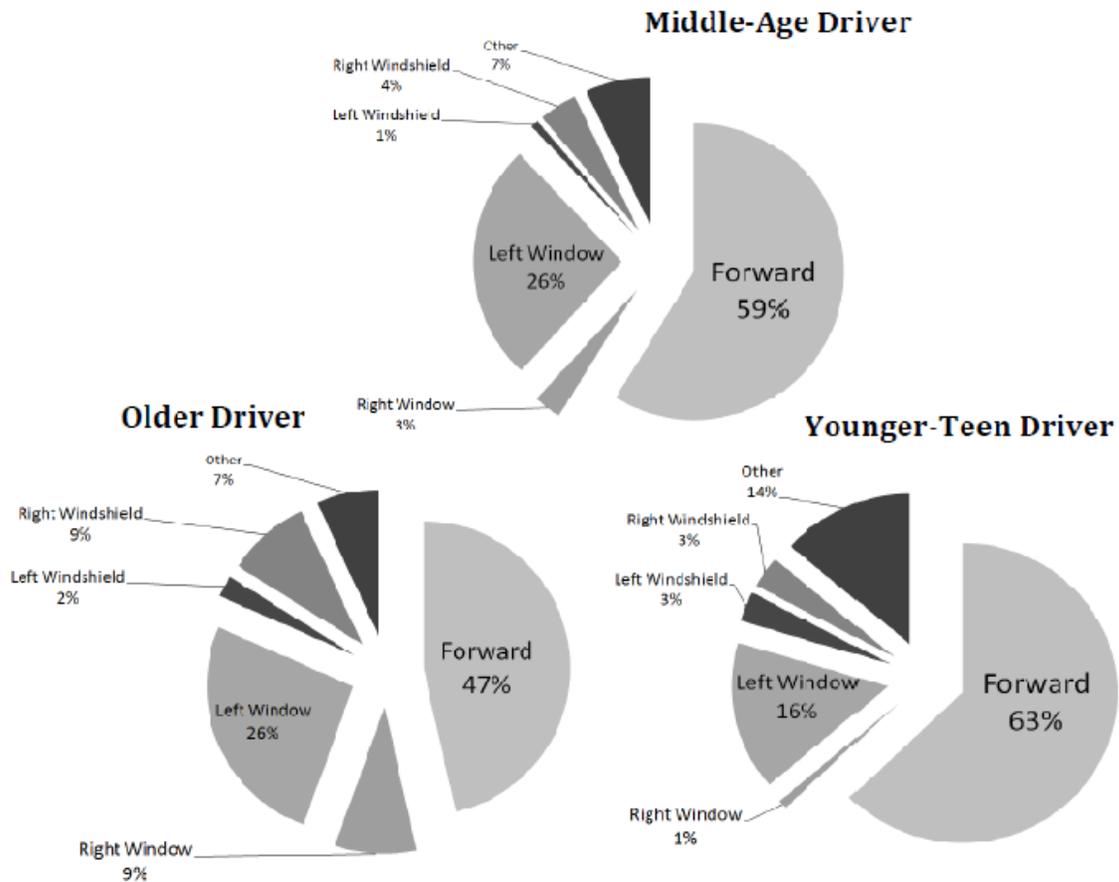


Figure 33. Chart. Distribution of glances for all age groups during right turns.

The right-turn glance distribution shows similarities to left-turn glances in the proportion of forward glances. However, for the left turn, there were approximately equal glance proportions between the left and right window. For the right turn, glances to the right window were negligibly reduced in comparison to the left-turn glances. This can be explained by the fact that while making a left turn into flowing or through traffic drivers need to check the traffic stream from the left as well, thereby checking their left window and then checking the traffic stream from the right, the lane into which the vehicle is going to merge. On the other hand, the percentage of right-window glances drops when making a right turn, as drivers are only concerned with the traffic approaching from the left and thus most glances are to the left window.

Transition Probabilities and Link Analysis

Link analysis was performed on the visual-scanning patterns of different driver age groups for both the left turn and right turn. Link analyses depict the sequence and probability with which drivers glance to different locations over a period of time (such as driving through an intersection). In this case, link analyses were done in order to discover whether the driver age groups scanned the intersections with the same pattern. In link analysis, two types of probabilities are calculated: (1) the probability of glancing at each of several locations, and (2) the probability of glancing from one location to another (in a particular direction), which is considered a link, and which help to reveal the sequence in which glances tend to occur from one

location to another within the larger pattern. These probabilities (for the links) were calculated as relative frequencies similar to the method used by Tijerina et al. (1997). The individual probability for each glance location (the nodes) was a ratio of the number of glance occurrences for a particular location to the total number of glance occurrences.

Figures 33, 34, and 35 provide the link diagrams for left turns within each of the three age groups, where the probability between two different glance locations is shown on the link between the two locations and the proportion of glances per location is shown inside the circle. When the visual glance reduction was carried out, 20 locations were coded, but not all of them are included in the link diagram. For purposes of a link analysis such as this one, it is useful to prune the links so that the most frequently traversed can be clearly seen and are not obscured by low-probability nodes and links that arise from the outlying tails of a group's glance-frequency distribution. Therefore, the inclusion rule applied in this analysis was twofold: (1) all locations were included in the link analysis if the link between them and any other glance locations was present with a frequency greater than 5% of the total number of link transitions between all locations for each age group; and (2) if a link went to or from one of the five "major" nodal glance locations, namely forward roadway, left windshield, left window, right windshield, and right window. These five were the locations to which a majority of the drivers had glances, and these locations were thus revealed in the data as important glance locations for the task of making unprotected intersection turns.

Overall, link diagrams show a very different driver performance characteristic than is usually captured by traditional statistics.

In Figure 33, the link analysis for middle-aged drivers, it is clear that visual scanning is highly organized. The focus is most often on the forward view; then middle-aged drivers tend to make a transition to the right windshield ($p = 0.35$), then to the right window ($p = 0.63$), then to the left window ($p = 0.65$), and then back to the right window ($p = 1$), and then finally back to the forward road ($p = 0.35$). This scan path enables middle-aged drivers to spend the most time and attention on the stream of traffic into which they must merge (toward the right) but still allows them to check the stream of traffic closest to them that must first be crossed (on the left).

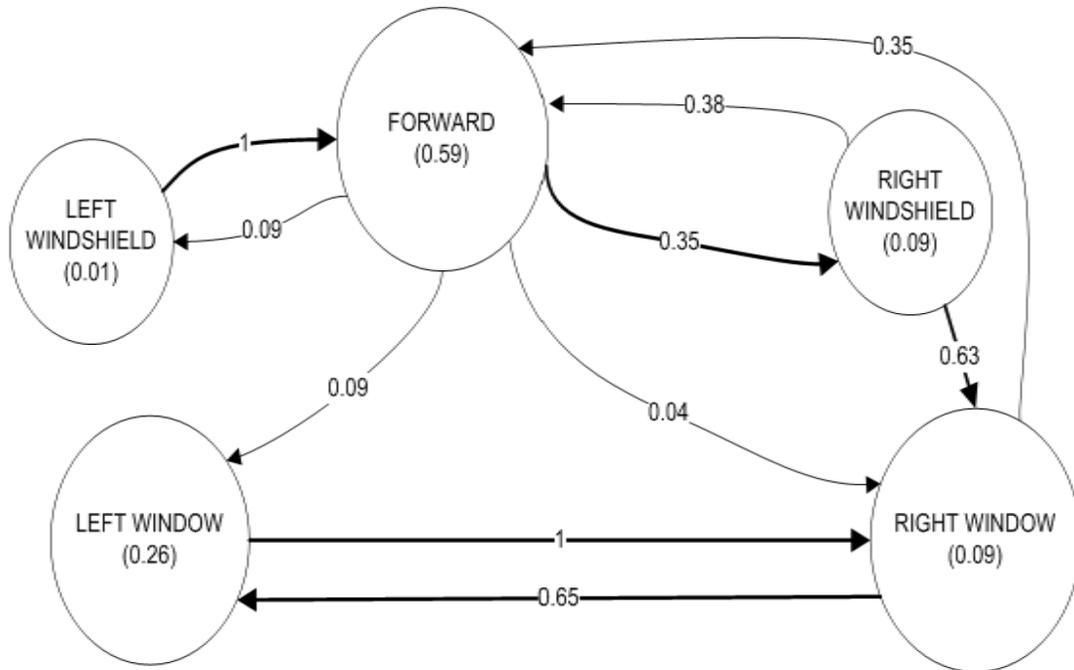


Figure 34. Diagram. Link analysis for middle-aged driver glances.

In Figure 34, the link analysis for older drivers, it is also clear that visual scanning is highly organized. The scan pattern for older drivers is very similar to that for middle-aged drivers except that it is narrower. After the older drivers move their eyes from the forward view to the right windshield, they less often extend their scans further out to the right window. Instead, they keep their scans somewhat more narrow, choosing to return back to the forward view ($p = 0.35$) rather than scanning out further to the right. They also look slightly less often toward the left window. In all other respects but these two, the older drivers' visual scan paths are similar to those of the middle-aged drivers.

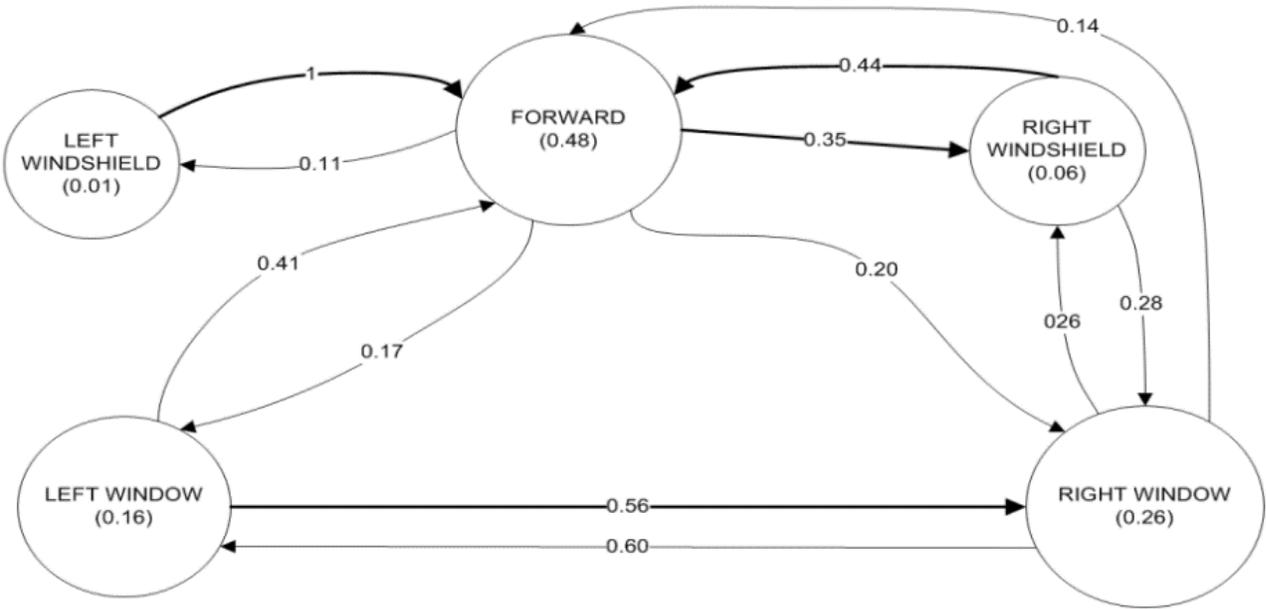


Figure 35. Diagram. Link analysis for older driver glances shows more-organized scanning (in comparison with link analyses for other driver groups).

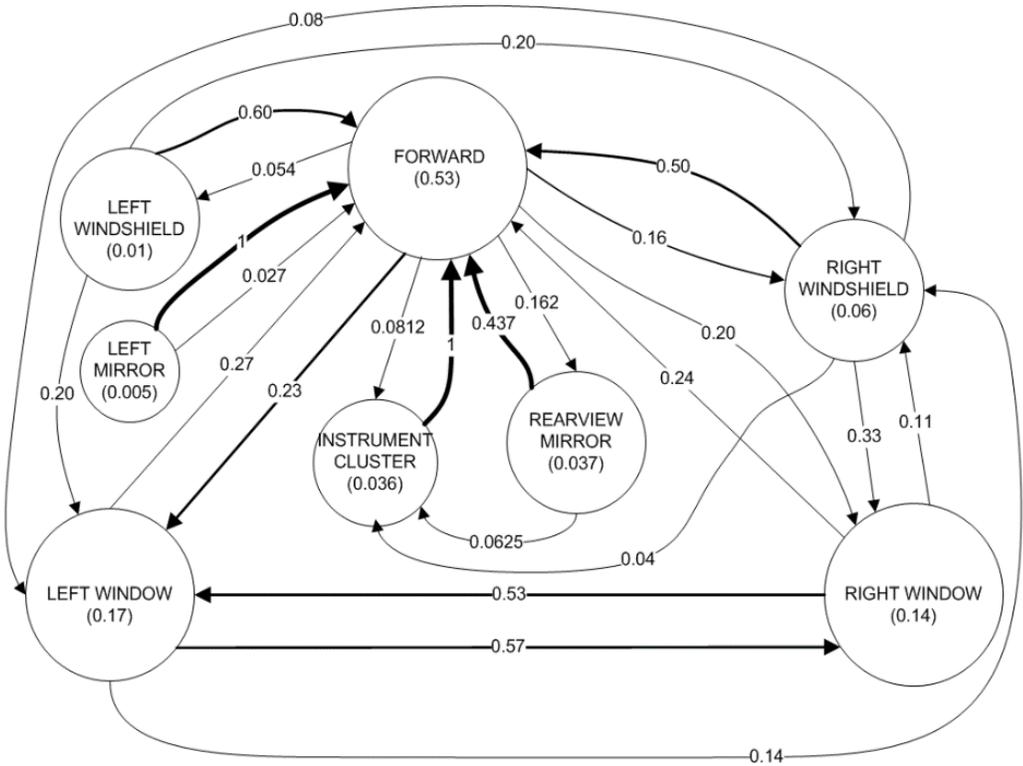


Figure 36. Diagram. Link analysis for younger driver glances shows broader and less-organized scanning (in comparison with link analyses for other driver groups).

As shown in Figure 35, the link analysis for younger drivers revealed a less-organized visual scan pattern, and a very different sequence of scanning. First, there was much more dispersion of glances among locations in the younger drivers' scanning than in the other driver groups. The links are also weaker, indicating more dispersion among younger drivers in the pattern of transitions they made from one location to another. Further, in terms of glance sequence, younger drivers were most likely to move from the forward view to the left window (but with a low probability of 0.23, indicating that some of the time they move to the right window ($p = 0.20$), and sometimes to areas through the right windshield ($p = 0.16$).

This is very different from what the experienced drivers in the middle-aged and older groups did. It indicates that their initial concern was with the traffic stream that they had to cross first, the one to left, rather than with the traffic stream in which they had to find a gap to turn into and merge. If the younger drivers checked areas through the right window (which happened with low probability), they moved to the left window with high probability (almost as high as the other age groups), and then returned back to the right window. There was also some disparity for transition from the right windshield to other locations for the younger drivers, who transitioned to many more areas from this one than did the other drivers. Their scan pattern raises the question of how they are able to complete gap estimation, given that their visual attention is allocated very differently from the other driver groups and does not seem aligned with where information lies in the environment for gap estimation.

The link analyses for right turns (though not included here) told a similar story for all three age groups except that the attentional shifts were to the other side of the turn (when turning right, glances tended to be focused leftward in the sequence).

Traffic Gap Acceptance and Rejection

The sizes of gaps accepted was analyzed using a 3×2 between-subject design, with three levels of Age Group (younger, middle-aged, older) and two levels of Traffic Density (present, absent).

The results indicated that older drivers tended to wait for larger gaps compared to the younger teen drivers for right turns. This may reflect a desire on their part to have more time to make the turn, in case they need it (given that they drive more slowly and may be aware of processing information more slowly). Differences by age approached but were only marginally significant, $F(2, 12) = 3.65, p = 0.057$. However, the sample of observations available for analysis was very small, so even marginally significant results are worth noting. (Analysis of gaps in naturalistic data presents a unique challenge for analysis since each gap is uniquely sized). Given that the main effect of Age Group was significant at $p < .10$, post hoc Student's *t*-tests were applied and showed that older drivers differed from younger drivers (see Figure 36). The more conservative Tukey HSD, however, did not show a difference (and this is shown as well in the coding at the bottom of Figure 36).

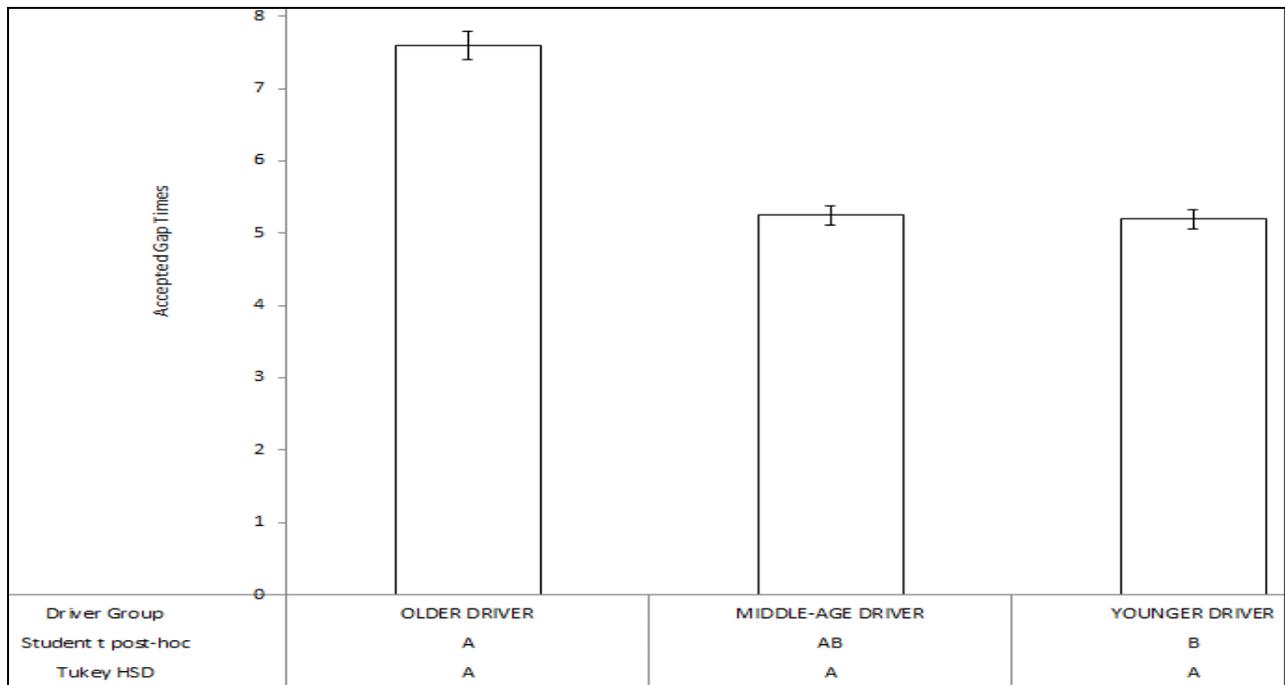


Figure 37. Chart. Accepted gap times by Age Group.

The sizes of gaps rejected by drivers (as being too short to allow a safe turn) were also analyzed. There was no significant main effect of Age Group for the rejected gap times.

Overall, analyzing gap-acceptance and gap-rejection behavior in naturalistic driving data is very complex due to the fact that the gaps that present themselves to the driver are not controlled for and are each unique, limiting the number of observations for each size of gap (and hence limiting the power to test statistically for differences). Given this limitation, descriptive data can be a useful source of insight (in the absence of definitive hypothesis testing). Therefore, Figure 37 presents the average length of gaps accepted and those rejected (not accepted) for each age group.

Analysis of the four kinematic variables revealed that during left turns there was a significant main effect of Age Group for peak speed and average speed through the intersection, $F(2, 15) = 4.59$, $p = .0278$, and $F(2, 15) = 6.34$, $p = .0101$. As indicated previously, peak speed is indicative of speed as the turn is completed and the vehicle returns to steady-state, straight-path driving. Average speed reflects speed across all three zones of the turn and thus is the only measure that is reflective of the overall turn maneuver. These results (in Figure 39) showed that older drivers used lower speeds throughout their turns (consistent with the findings of Phase 1) and completed their turns at lower speeds than any other age group. Younger drivers used higher speeds throughout their turns, including at the completion of their turns. Tukey HSD post hoc test results are displayed in the Figure 39.

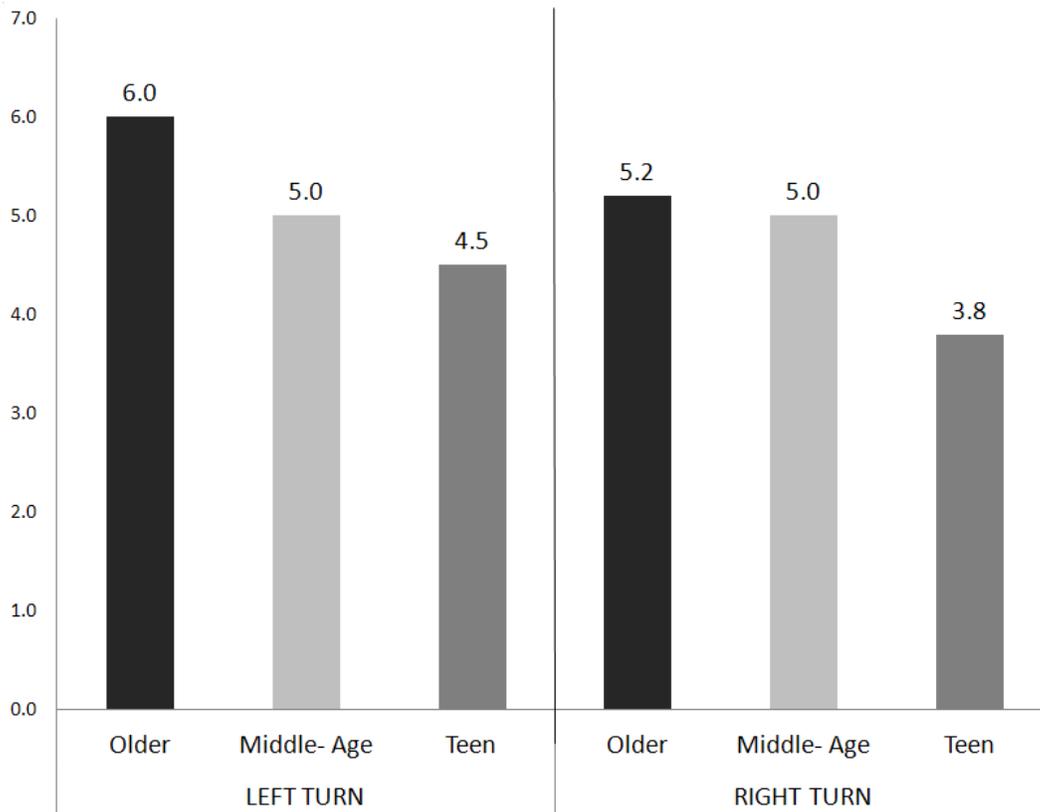


Figure 38. Chart. Smallest accepted gaps (in seconds) for all age groups while making left and right turns.

Additional analyses done to explore the effects of traffic density and any potential interactions with age-group effects revealed a main effect of traffic density on peak speed, $F(1, 12) = 6.37$, $p = .0267$, and an interaction of Age Group and Traffic Density on peak lateral acceleration, $F(1, 12) = 5.10$, $p = .0250$ for left turns. In the presence of traffic, drivers tended to execute the turn at a faster rate, thereby generating more peak lateral acceleration, except for older drivers (whose peak lateral acceleration was quite low in the presence of traffic). This interaction is depicted graphically in Figure 40. This, again, indicates that older drivers are either very cautious or are slowed by the effects of aging. However, if this were due to age-related slowing on their responses, it should affect their peak lateral acceleration in the no-traffic condition, which it did not. Their speed in executing the turn when no traffic was present is not statistically different from that of middle-aged drivers. Given this, it would appear that when traffic is present at the intersection that older drivers' choice of slow speed in executing the turn is a deliberate and strategic choice, perhaps arising out of a desire to be careful and perhaps out of an attempt to prevent a crash. Ironically, it may also be a choice that unintentionally lengthens the time older drivers are in the zone of conflict and exposed to crash risk and does so under conditions when other traffic is present.

Younger drivers, on the other hand, had a lower peak lateral acceleration mean value in the absence of traffic in comparison to the presence of traffic. (Their peak lateral acceleration in the presence of traffic was similar to that of middle-aged drivers). However, the mean peak lateral

acceleration in the absence of traffic for younger drivers was significantly lower than that of the drivers in the other age groups.

Driving Behavior (Kinematic Variables)

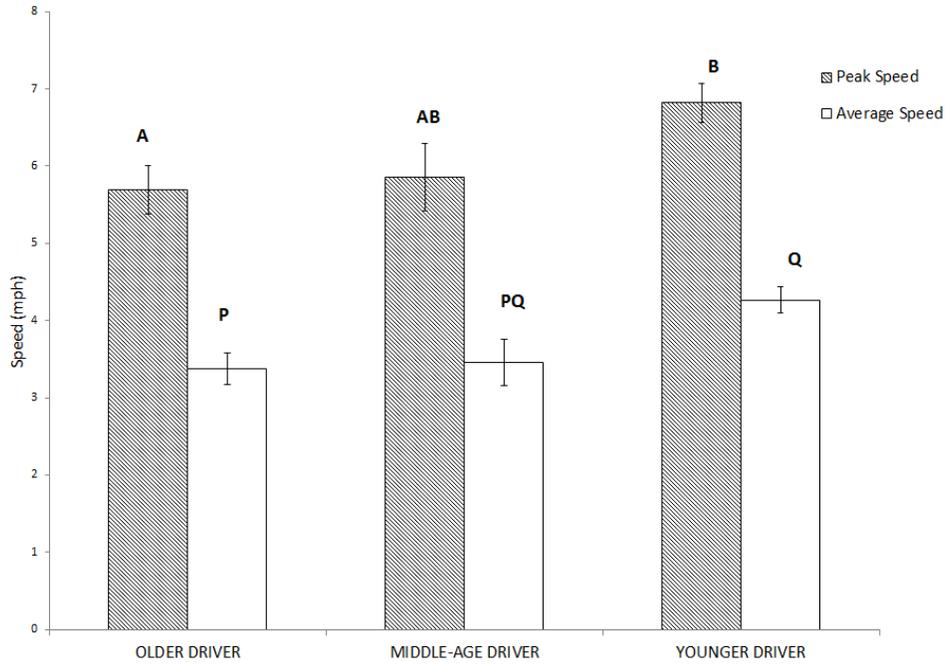


Figure 39. Chart. Peak speed and average speed means for left turns.

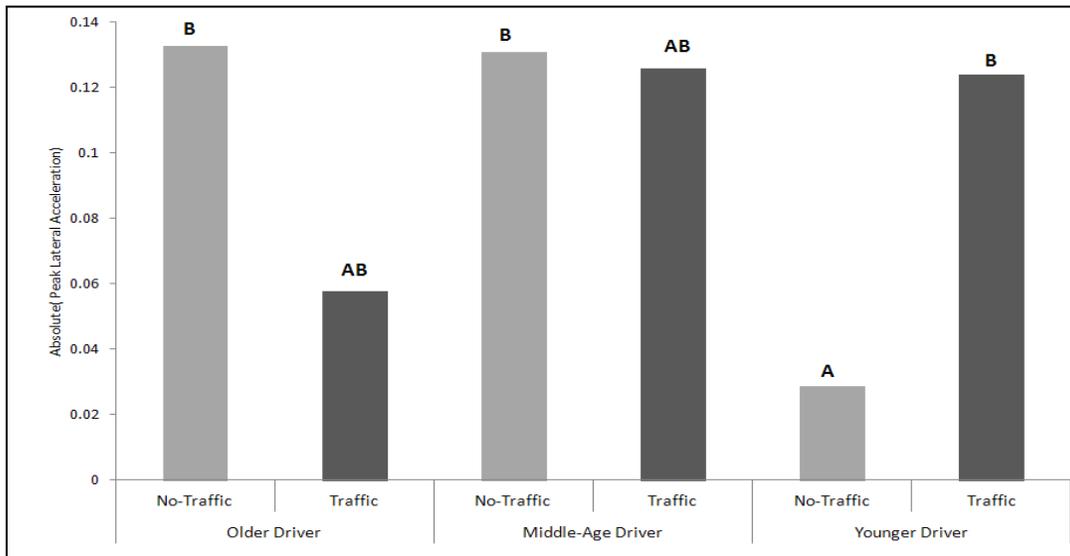


Figure 40. Chart. Peak lateral acceleration during left turn (associated with zone of conflict).

DISCUSSION AND CONCLUSIONS FROM PHASE 2

Overall, Phase 2 of the project provided additional analyses to illuminate differences between driver age groups during the negotiation of unprotected turns. The largest differences in driving performance existed predominantly between the older and younger driver groups.

These efforts, and the effects of traffic levels, gap acceptance, and gap rejection that were found, should be considered exploratory only and seen as ventures into new areas of analysis using naturalistic data. Although two naturalistic data sets were combined, the number of observations was still very limited for many cells of the analyses, limiting statistical power to detect significant effects. Even though some findings were only exploratory, they are nonetheless important in suggesting new avenues for further examination. As more naturalistic data become available (e.g., through SHRP 2), the preliminary findings and new hypotheses generated from this work can be reexamined with more robustness using the new methods developed in this undertaking.

The findings from Phase 2 extended the findings from the first phase of this project. To recap, findings from the first phase were related to driver visual scanning (that included both eye behavior and head-turning behavior) as well as vehicle control behavior (speed through intersections). Visual scanning and head rotation during left turns and some aspects of driving performance differed between drivers in different age groups (older, middle-aged, and teenaged). However, these differences were not as simple as initially thought (some appeared to be unique to types of intersections). Nonetheless, the patterns of behavior that were identified are likely to provide useful input toward future traffic safety goals for both aging drivers and teenaged drivers.

Phase 2 provided the following additional findings.

Younger Driver Scanning

When no traffic was present at the intersection, younger drivers scanned more narrowly than other driver groups. However, when traffic was present at the intersection, the opposite was observed. Younger drivers scanned more broadly. However, the link analysis for younger drivers revealed that the scan pattern of younger drivers was much less organized (or at least more dispersed) than that for middle-aged and older drivers, and much less strategic in gathering important information from the intersection needed for turning. This is contrary to the findings of Bao and Boyle (2009).

Older Driver Scanning

In contrast with younger drivers, older drivers spent a slightly greater proportion of time looking at the traffic stream into which they had to merge (where they had to choose a gap large enough to accommodate a turn-and-merge maneuver into the stream of traffic), which is also the same stream of traffic which could strike them during a turn if an error in judgment were made in this process. (Of course, they also had to check the traffic stream from the other side that first had to be crossed safely, which they did with a lower proportion of glances and attention, as did the

middle-aged drivers.) However, the scan of older drivers was more narrowly focused than that of middle-aged drivers and focused on the traffic stream into which they needed to merge.

The link analysis revealed that older drivers had a highly organized scan pattern, which was similar in many ways to that of middle-aged drivers. However, their scan paths were more narrowly focused and were consistent with the data on head turning from Phase 1. Their scan paths appeared consistent with the highest-priority information-gathering needs for preparing and making a left turn. However, older drivers may less often sample areas where unexpected or infrequent hazards could arise.

It is worth noting that Summala et al. (1996) also found a similar pattern of attention allocation in drivers making turns. For example, Summala found that drivers were less likely to check their right-hand side before executing a right-turn maneuver when compared to left-turn maneuvers (they instead allocated most attention to the left prior to a right turn) and vice versa for a left turn. The results reported here are consistent with the Summala et al. (1996) findings that drivers adopt a strategy of allocating most of their visual scanning and attention to the direction of major threats during turns (with less allocated to regions representing more minor or less-frequent sources of hazard) and that older drivers show a more pronounced form of this strategy than middle-aged drivers. Bao and Boyle point out that this can be a concern since failure to look both ways appropriately may increase the likelihood of collisions into unobserved objects or unanticipated pedestrians located on the less-attended side. While this may be true, the issue is really what balance in the probabilities of scanning across regions (and what sequence of scanning) best reflects an appropriate, safe, and efficient strategy for drivers to use for turns of different types. These strategies are likely developed by drivers as a function of their own driving experience, and may well be further adapted as they encounter each new intersection.

Checking the rearview mirror was identified by Bao and Boyle as indicative of the driver's ability to attend to environmental situations as well as oncoming traffic. They found age-group differences (with middle-aged drivers checking more, especially during straight crossing maneuvers). They interpreted this to mean that middle-aged drivers have a greater awareness of their surrounding environment. However, it is not at all clear that time spent sampling the rearview mirror during a turn's zone of initiation or zone of conflict is an appropriate allocation of visual attention at that time. There would not appear to be any information in the rearview mirror that would assist the driver with the time-urgent matter of preparing for or executing the turn in these zones. Thus, it would not seem adaptive to sample the rearview mirror during these zones of the turn. If rearview mirror glances are relevant at any time during turns, then it is perhaps during the zone of completion when drivers might become concerned about whether they have completed the turn with too small of a gap behind them to traffic now closing on their vehicle from the rear. They may choose to check the rear view to confirm that they are safe and that a rear-end crash is not imminent. Indeed, this is the pattern that was observed in the naturalistic data. Glances to the rear increased in the zone of completion. This would appear to be a strategic response to the phase of the turn. Both older and middle-aged drivers showed this response in the zone of completion for the signalized intersection in the research reported here.

Driver Behavior – Older vs. Younger Drivers

The most important finding about driving behavior (using kinematic measures) from Phase 2 was the confirmation of the Phase 1 finding that older drivers use slower speeds to proceed through intersections and, more importantly, that they specifically execute the turn itself at slower speed when in the presence of traffic (but not when traffic is absent). Older drivers' choice of slow speed in executing the turn thus emerges as a deliberate and strategic choice (perhaps arising out of a desire to be careful and perhaps out of an attempt to prevent crash). As noted previously, it may also be a choice that unintentionally lengthens the time during which the older drivers are in the zone of conflict and exposed to crash risk and does so under conditions when other traffic is present. However, whether or not this could lead to increased risk could not be observed in this study, given that no crashes occurred at the intersection under analysis. However, this would be an interesting follow-up question as other naturalistic data become available.

Furthermore, older drivers wait for longer gaps through which to make their turns in traffic, both for left turns and for right turns (whereas other age groups accept shorter gaps for right turns).

CHAPTER 5. GENERAL DISCUSSION

Findings from the naturalistic driving research within this project extend findings in the literature about driver behavior during turns at intersections. Based on the results of the research reported here, a clearer picture is now emerging of age-related differences in making turns at intersections. These differences are distinct for younger drivers and older drivers. The findings suggest entirely different vulnerabilities to risk during turns for the different age groups.

These results can be useful toward supporting traffic-safety goals through the development of countermeasures for both aging drivers and teen drivers. In addition, the project has identified important avenues for future research as more naturalistic data become available (e.g., through the SHRP 2 Naturalistic Driving Study). Finally, a set of methods and techniques developed for this project can now be made available for use on future projects.

SUMMARY AND DISCUSSION OF SPECIFIC FINDINGS

This research extends the state-of-the-art understanding of how drivers behave when making left turns at intersections.

It reveals that while different ages scan differently, scan patterns are uniquely affected by turn-specific variables. These factors include whether or not there is a stream of oncoming, through traffic (e.g., four-way vs. three-way intersection), whether any traffic control is present (signs or signals), and whether the traffic control offers protection for the turn, direction of the turn, and density of the traffic at the time of the turn, among other factors. Visual processing undertaken by drivers is also affected by the different information needs and demands as they progress through the zones of a turn: from the zone of initiation (where the driver must choose a gap through which to turn), through the zone of conflict (in which the driver steers the vehicle along the turn path through the gap in traffic), to the zone of completion (where the driver continues in the new direction of travel). As a result:

- Visual scanning differences by age are not as simple as studying one intersection and turn type, and then generalizing findings across age (as many experimental studies have tended to do). To fully understand driver scanning, multiple types of intersections and turns must be examined.
- In this work, several age-related differences in scanning were found. Scan patterns of different age groups were uniquely affected by turn-specific variables even when turn types were matched. Scan patterns were also affected by changing information needs and demands as a driver progressed through the zones of a turn. For example, a pattern of looking more at the forward path while in the intersection for a left turn was most pronounced when an intersection had oncoming traffic that was moving through the intersection toward the left-turning driver's vehicle and there were no traffic lights to protect the turn. But this pattern differed for different intersections (consistent with findings by Bao and Boyle, 2007, 2009). Scanning also differed with the type of information processing required in each zone of the intersection. In the zone of initiation, the durations of glances were longest. This is the zone during which gap estimation and selection is most likely done, and hence glance durations likely lengthen in order to

extract information needed for this estimation and decision process. In the zone of conflict, the proportion of glances to the forward area/forward path of the vehicle was highest. This seems strategic, since this is where the driver is steering the vehicle along the turn path (and looking at and around the path along which they are steering the vehicle). Link analyses (in Phase 2) revealed that there was a clear sequence of glancing from area to area for middle-aged and older drivers, beginning with the forward area and proceeding to rightward areas (for left turns). Older drivers tended to concentrate more narrowly on the rightward area nearest the forward view, whereas middle-aged drivers scanned a bit more broadly to the right. Both driver groups also occasionally scanned to the left (since traffic from the left had to be crossed as well). (This pattern was reversed for right turns). However, those glances were fewer in proportion and sampled less often in the sequence. These results are highly consistent with the findings of Summala et al. (1996), who similarly found that drivers exhibit strategic visual scanning and attentional allocation to the side of the turn from which major threats come (e.g., toward the oncoming traffic stream into or through which they must turn), spending less time on areas in which minor or less frequent hazards might arise. Younger drivers, on the other hand, showed much less organization in their scans. All driver groups demonstrated a broadening of scanning (to more areas) when traffic becomes present around them, and this effect was most pronounced for younger drivers.

- Analyses of head rotation, or head turning, made unique contributions to visual scanning (beyond what the eyes scan) and showed age-related differences. The head-turning data showed that the extent of head turning for older drivers is narrower than for the other age groups (at least for the drivers and turns examined thus far) and may be oriented differently than for middle-aged drivers. Analysis of pre-study measurements of neck flexibility confirmed a loss of an average of 19 to 26 degrees of head rotation flexibility as a function of age, consistent with aging norms of 4 degrees of lost neck flexibility per decade of age, but this loss did not account for the extent of narrowing in head rotation shown during turns. Older drivers used only 30 degrees of the head-turning flexibility of which they were capable, suggesting that their head-turning behavior reflected an attentional strategy, not a physical limitation.
- This research also deepened knowledge about the kinematics of how drivers control their vehicles through turns (by examining a set of driving performance measures). Analyses revealed consistent age-related differences in intersection-traversal behavior in both Phases 1 and 2. The driving performance measures analyzed included approach speeds to the intersections, speed through the intersections, and time spent in (i.e., driving through) the intersections. Speed through the intersections was significantly different. The slowest speeds were observed at the intersection that was unprotected and had no signal or sign, and no through traffic. Additionally, the older participants drove through the intersections at slower speeds while teens drove faster. The difference between age groups was pronounced when the intersection was non-signalized. One particularly interesting finding from these speed differences was that the slower speeds taken by older drivers meant that they tended to spend more time in the zone of conflict for the intersections. Given that speeds were adapted by intersection type (with the slowest speeds observed at the intersections having the least signage and protection), it would appear that this driving

behavior reflects an awareness of risk on the part of the middle-aged and older drivers, and an attempt to compensate for it. It is rather unfortunate that while slowing in the zone of initiation may be helpful to compensate for risk, excessive slowing in the zone of conflict could have the unintended consequence of increasing risk (by extending exposure to traffic from the oncoming stream). However, it is not clear that the extent of slowing by older drivers could be considered “excessive” since no crashes or near-crashes were observed in any of these epochs.

IMPLICATIONS FOR SUPPORT OF SAFETY GOALS AND COUNTERMEASURES

The findings from this research suggest that support for safety goals and countermeasure development should be tailored by age group.

The behavior of older drivers appears highly strategic in nature. (Even the narrowed extent of the scan, with a rightward orientation during left turns appears to be strategic in nature). The changes in scanning exhibited by older drivers simply appear to be more specific, more focused “versions” of the visual scanning typical of middle-aged drivers, tuned specifically to areas of the highest perceived threat during turns. However, it is possible that this may lead to some neglect of other areas that, while perhaps less salient, are still very important and if entirely neglected (or if responded to in a manner that is too slow) could contribute to elevated risk of crash during turns (e.g., if unnoticed traffic or pedestrians are present in these areas). In addition, it is still possible that age-related changes in perception and cognition may be contributing to some aspects of these changes in visual scanning and behavior at intersections (e.g., slowing down or lengthening the time spent to process visual information and estimate gaps, choosing very long gaps, and driving slowly).

Thus, even when there are observed behavioral differences, it is not always a simple task to identify which behavioral pattern is the most adaptive or lowest risk. Similarly, what these differences suggest about countermeasures for older drivers is still somewhat difficult to identify, especially given that scanning strategies appear to be affected by intersection-specific features (geometries, clutter, traffic densities, etc.). However, older drivers may benefit from in-vehicle support for gap estimation (should that ever become available) and may potentially benefit from warnings about cross-traffic in areas that tend to be neglected by their scan patterns (though this would need to be studied empirically as such alerts could conceivably have unintended consequences).

For younger drivers, it may be possible to coach or train improved visual scanning during turns at intersections as part of their training (or graduated driver’s licensing experiences). An improved sequencing of the areas viewed may be something that could be taught through directed video training or perhaps other types of appropriate training designed to facilitate learning about gap estimation and hazard recognition.

FUTURE RESEARCH

As more research is done to deepen the scientific understanding of how drivers of all ages approach and execute turns of different types, it will be important to continue to utilize naturalistic data. However, this effort will require harnessing large quantities of such data in

order to be able to perform analyses with adequate statistical power at specific intersections. The SHRP 2 database will potentially become an excellent source of such data and could even be pooled with other databases. A broad range of intersections, turn types, and driver ages must be examined in naturalistic work to make further progress. One of the big lessons learned has been that extracting an experimental design that permits analysis of like-intersections and similar scanning conditions is difficult using this paradigm. Thousands of records must be searched, which even then may only yield a small set of data to analyze that may end up being very sparse on some desired dimensions of analysis (e.g., amount of traffic present at the time of turn). This underscores the importance of large naturalistic databases such as the SHRP 2 database (or pooling of two or more databases).

In future research it may be beneficial to study some intersections for which crash incidence and other data are known. This would enable scientists to begin to identify which of the changes in visual scanning and attentional shifts (if any) may be related to factors that elevate the risk of specific crash types during the turns, such as willingness to engage in secondary tasks and the potential for distraction which might follow.

For instance, Charlton et al. (2012) performed an analysis comparing naturalistic driving data collected from seniors at Australian and U.S. intersections. The goal was to explore seniors' willingness to engage in secondary tasks while traversing an intersection. Each data collection effort involved 10 participants (6 male, 4 female) with similar age ranges (65–83 in Australia vs. 71–83 in the U.S.). In all, the study looked at 200 intersection traversals for the 10 participants in each country. Figure 41 illustrates the intersection type distributions.

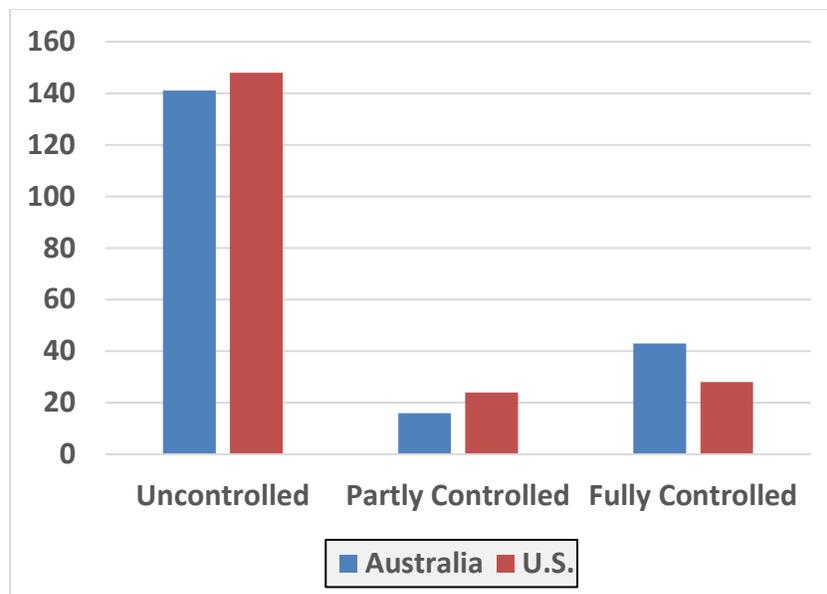


Figure 41. Chart. Intersection type distributions.

Results showed that grooming and talking were the two highest-frequency secondary tasks across both groups, though not in the same order. Grooming was the highest in Australia, almost double the number for talking. In the U.S., talking was the most frequently observed secondary task, occurring approximately four times more often than grooming. Both samples demonstrated

notable increases in willingness to engage in secondary tasks at fully controlled versus uncontrolled intersections; this demonstrates that seniors in both countries tended to logically and strategically allocate resources to secondary tasks while driving.

One interesting difference observed between the two samples was related to mobile device usage while the vehicle was moving. None of those in the Australian sample were observed to use a mobile device, whereas five instances of mobile device usage were observed in the U.S. sample. Furthermore, the mean duration for this task (10.72 s) was more than twice that of the second-longest average duration task of talking/singing.

FIVE NEW METHODS PRODUCED BY THE PROJECT

This research extended VTTI's methodological capabilities for studying driver behavior at intersections. It is hoped that these methods will prove helpful to others who may be undertaking work in this domain. The five new methods that were produced during the course of this work were:

1. Algorithms for finding intersections and turns of matched types;
2. A method for using MASK data to depict the spatial extent of head rotations;
3. A method for depicting the spatial distribution of Glance Locations \times Durations;
4. Methods for quantifying traffic at intersections;
5. Methods for identifying gap-acceptance behaviors for analysis.

CONCLUDING REMARKS

Overall, this research program with naturalistic data has revealed that older drivers are strategic in their behavior during turns at intersections and attempt to drive with care, applying scanning strategies that appear matched (based on their experience) to the information needs of the turns, and using slower speeds (perhaps with the intention of providing an extra measure of safety). However, there may be some hidden risks in the strategies they have adopted in an effort to drive cautiously and strategically. These risks must be examined scientifically with follow-on work. In contrast, younger drivers exhibit visual scanning and driving behaviors that are different from other age groups that reflect their inexperience. It is likely that these results can begin to guide the development of assistance for both groups as research in these areas continues.

APPENDIX A. CALCULATION OF VISUAL ENTROPY

The method and calculation used for visual entropy is given below. It is based on glance locations that were coded from video (shown in the leftmost column). The second column shows p , the proportion of glances exhibited in each location (these are illustrative values). The third column shows the log of these proportions. The fourth column shows the computation of entropy, based on the formula for entropy given below the chart (which originates from Shannon's original formula). Note that after the values in column #4 are summed, the absolute value of the sum is taken as the entropy value.

Entropy (E) in bits is defined as:

$$E_{\text{bits}} = -\sum_{i=1}^n p_i \log p_i$$

where,

n = the total number of possible predefined glance locations; and

p_i = the probability of a single glance landing on the i^{th} predefined glance location.

Note that for any $p_i = 0$, we define $p_i \log p_i = 0$, which is consistent with the well-known limit of this equation as p_i approaches zero.

A sample computation is provided below:

SAMPLE COMPUTATION OF ENTROPY				
GLANCE LOCATION	p Proportion Glances to LOCATION	log of p	product	
Forward	0.50	-0.30103	-0.150514998	
Left W/S	0.25	-0.60205999	-0.150514998	
Left W/ow	0.00	0	0	
Right W/S	0.25	-0.60205999	-0.150514998	
Right W/ow	0.00	0	0	
Sum			-0.451544993	
			ENTROPY VALUE or INFO VALUE (in bits)	
			(absolute value of this cell)	

Citations providing useful background information (from the aviation domain) are:

Itoh, Y., Hayashi, Y., Tsukui, I., & Saito, S. (1990). The ergonomic evaluation of eye movement and mental workload in aircraft pilots. *Ergonomics* 33(6), 719–733.

Tole, J. R., Stephens, A. T., Vivaudou, M., Ephrath, A. R., & Young, L. R. (1983). Visual scanning behavior and pilot workload (No. NASA-CR-3717): Washington, DC: NASA.

REFERENCES

- Aich, S. (2011). *Evaluation of driver performance while making unprotected intersection turn utilizing naturalistic data integration methods* (Master's thesis). Virginia Tech, Industrial and Systems Engineering, Blacksburg, VA.
- Antin, J. F., Lockhart, T. E., Stanley, L. M., & Guo, F. (2012). Comparing the impairment profiles of older drivers and non-drivers: Toward the development of a fitness-to-drive model. *Safety Science*, *50*(2), 333-341.
- Bao, S., & Boyle, L. N. (2007). Visual search strategies of older drivers at rural expressway intersections. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *51*, 1560.
- Bao, S., & Boyle, L. N. (2009). Age-related differences in visual scanning at median-divided highway intersections in rural areas. *Accident Analysis & Prevention*, *41*(1), 146-152.
- Braitman, K. A., Kirley, B. B., McCartt, A. T., and Chaudhary, N. K. (2007). Crashes of novice teenage drivers: Characteristics and contributing factors. *Journal of Safety Research*, *39*(1), 47-54.
- Charlton, J. L., Antin, J. F., Catchlove, M., Guo, F., Scully, M., Koppel, S., & Verdoorn, A. (2012, August). *Older drivers, intersections and distraction: A comparison of US-Australian data*. Presentation given at the Naturalistic Driving Symposium, Blacksburg, VA.
- Federal Highway Administration. (2009). *The national intersection safety problem* (Intersection Safety Issue Brief No. 2). Washington, DC: Author.
- Fildes, B., Charlton, J. L., Koppel, S., Andrea, D., & Hammer, M. (2006, July). *Visual search strategies among older and younger drivers*. Vision in Vehicles conference, Dublin, Ireland.
- Gazzaley, A., Cooney, J. W., Rissman, J., & D'Esposito, M. (2005). Top-down suppression deficit underlies working memory impairment in normal aging. *Nature Neuroscience*, *8*(10), 1298-1300.
- Gazzaley, A., Rissman, J., Cooney, J. W., Rutman, A., Seibert, T., Clapp, W., & D'Esposito, M. (2007). Functional interactions between prefrontal and visual association cortex contribute to top-down modulation of visual processing. *Cerebral Cortex*, *17*, 125-35.
- Gordon, T., Nobukawa, K., Barnes, M., and Goodsell, R. (2009). *Analysis of left-turn gap acceptance at signalized intersections using naturalistic driving data* (Interim research report, FHWA contract #DTFH61-05-H-00021). Ann Arbor, MI: University of Michigan Transportation Research Institute. Retrieved from http://www.researchgate.net/profile/Kazutoshi_Nobukawa/publication/272481585_ANALYSIS_OF_LEFT-

[TURN GAP ACCEPTANCE AT SIGNALIZED INTERSECTIONS USING NATURALISTIC DRIVING DATA/links/54e52a6d0cf22703d5c083b4.pdf](https://www.nhtsa.gov/sites/nhtsa.nhtsa.gov/media/1044/turn_gap_acceptance_at_signalized_intersections_using_naturalistic_driving_data/links/54e52a6d0cf22703d5c083b4.pdf)

- Klauer, S. G., Simons-Morton, B., Lee, S. E., Ouimet, M. C., Howard, E. H., & Dingus, T. A. (2011). Novice drivers' exposure to known risk factors during the first 18 months of licensure: the effect of vehicle ownership. *Traffic Injury Prevention, 12*(2), 159-168.
- Lee, S. E., Klauer, S. G., Olsen, E. C., Simons-Morton, B. G., Dingus, T. A., Ramsey, D. J., & Ouimet, M. C. (2008). Detection of road hazards by novice teen and experienced adult drivers. *Transportation Research Record: Journal of the Transportation Research Board, 2078*(1), 26-32.
- McGwin, G., & Brown, D. B. (1999). Characteristics of traffic crashes among young, middle-aged, and older drivers. *Accident Analysis and Prevention, 31*, 181-198.
- Preusser, D. F., Williams, A. F., Ferguson, S. A., Ulmer, R. G., & Weinstein, H. B. (1998). Fatal crash risk for older drivers at intersections. *Accident Analysis and Prevention, 30*(2), 151-159.
- Romoser, M., Fisher, D. L., Mourant, R. R., Wachtel, J., & Sizov, K. A. (2005, June). *The use of a driving simulator to assess senior driver performance: Increasing situational awareness through post-drive one-on-one advisement*. 3rd International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design, Rockport, ME.
- Romoser, M., & Fisher, D. L. (2009). Effects of cognitive and physical decline on older drivers' side-to-side scanning for hazards while executing turns. In *Proceedings of the Fifth International Driving symposium on Human Factors in Driver Assessment, Training and Vehicle Design*.
- Summala, H., Pasanen, E., Rasanen, M., & Sievanen, J. (1996). Bicycle accidents and driver's visual search at left and right turns. *Accident Analysis and Prevention, 28*(2), 147-153.
- Staplin, L., Lococo, K., Byington, S., & Harkey, D. (2001). *Guidelines and recommendations to accommodate older drivers and pedestrians* (Publication No. FHWA-RD-01-051). Washington, DC: U.S. Department of Transportation, Federal Highway Administration.
- Stutts, J., Martell, C., & Staplin, L. (2009). *Identifying behaviors and situations associated with increased crash risk for older drivers* (No. HS-811 093). Washington, DC: National Highway Traffic Safety Administration.
- Tijerina, L., Garrott, R. W., Glecker, M., Stoltzfus, D., & Parmer, E. (1997). *Van and passenger car driver eye glance behavior during lane change decision phase*. Washington, DC: National Highway Traffic Safety Administration.