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The Impact of Intersection Design on Simulated Driving Performance of Young and Senior Adults

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Purpose. *The Federal Highway Administration (FHWA) proposed guidelines for highway design to increase the safe driving ability of older drivers; however, little empirical evidence exists to support the effectiveness of these guidelines. The purpose of this study was to investigate the effects of implementing these guidelines (in 4 pairs of intersections) on safe driving performance of older and younger drivers using a high-fidelity driving simulator.*

Design and Methods. *We replicated four intersection pairs (improved versus unimproved) in a high-fidelity, virtual reality driving simulator. Simulator scenarios were created from actual road locations, replicating road geometrics and traffic control devices. The simulator's controls were integrated with an actual vehicle to make the driving experience as realistic as possible. Kinematic measures were obtained from the simulator in conjunction with driving errors recorded by trained driving evaluators sitting in the cab of the car. Thirty-nine subjects, 19 younger and 20 older adults, participated in the study.*

Results. *For the kinematic data we found greater lateral control, as indicated by significantly smaller maximum yaw during the turn phase, at all of the improved intersections when compared to the unimproved intersections. We found some significant age differences, but mostly in only one of the intersection-pairs. For the behavioral data, there were significant differences in driving errors between improved and unimproved intersections in two intersection-pairs; however, there were no significant differences in driving errors between the older and younger drivers.*

Implications. *The findings suggest that both young and older drivers may benefit from roadways with safety features recommended by the FHWA guidelines as indicated by the increased lateral control of the vehicle when negotiating these intersections. These findings generate critical information for those involved in the design of roadway systems.*

Keywords Older, Younger Drivers; Driving Simulator; Driving Kinematics; Roadway Infrastructure; Highway Safety; Intersection Design

There are currently over 35.9 million Americans over the age of 65. This portion of the population has grown rapidly in the past 100 years and will double over the next 30 years (He et al., 2005). Thus, more older drivers than ever before are currently on the roadways (Centers for Disease Control and Prevention, 2002; NHTSA, 2003). Older drivers are at an increased risk for unsafe driving behaviors and crashes due to age-related physiological changes, frailty, multiple chronic diseases, and medications (Dellinger, Langlois, & Li, 2002; Eberhard, 1996; McGwin et al., 2000; McKnight & McKnight, 1999). There is, therefore, a need to evaluate their driving performance.

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Various clinical evaluations that are used to indicate driving-related skills, such as mental capacity, attention, and reaction time, do not reliably predict on-road driving performance (McGwin et al., 2000). On the other hand, on-road driving evaluations, which assess driving safety, are costly, time consuming (Di Stefano & Macdonald, 2006), and may be unsafe depending on the condition of the driver. Various conditions, such as dementia and legal blindness, may make these on-the-road assessments risky (Lee, Lee, & Cameron, 2003). In addition, the older driver group is at the highest risk of all adult drivers for injuries from car crashes (NHTSA, 2006). Thus, it seems necessary to find an alternative way for testing driving performance of older drivers.

Driving simulators use computer-based technology to create the impression of driving a vehicle and may provide an alternative to on-road assessments. High-risk clients can be tested in a driving simulator under safe conditions in which errors can be made without cost to life or property. In addition, driving simulators allow for well-controlled and repeatable conditions (Rizzo, Jermeland et al., 2002; Stern & Davis, 2006), which makes them a promising evaluation and research tool. However, simulators have a couple disadvantages. First, they have not been validated as reliable predictors of on-road driving performance. Second, simulator sickness, a type of motion sickness, is experienced by some people when "driving" a simulator (Mourant & Thattacherry, 2000). The symptoms of simulator sickness may include dizziness, headache, nausea, and vomiting (Stern & Koch, 1996; Murray, 1997). Obviously, a driver would be compromised when experiencing these symptoms, and thus a driving evaluation in a simulator may not be appropriate for all drivers.

Researchers have used various methods to assess driving safety including collecting crash rates (Dellinger et al., 2002; NHTSA, 2004; Treat, Tumbas, McDonald et Al., 1977), recording driving errors during on-road evaluations (Classen et al., 2005; Di Stefano, 2003; Justiss, 2006; Shechtman et al., 2005), and using drivers' self-reports (Shinar, Schechtman, & Compton, 2001). Although examining crash rates is the most accurate method to assess driving safety, it may be impossible or impractical to use this method to indicate the safety of specific roadway intersections. Instead, assessing on-road driving performance at specific intersections may be substituted to indicate driving safety. Thus, driving performance can be used as a surrogate measure of driving safety. Driving performance is commonly assessed by trained evaluators who sit in the car and record driving errors as the driver transverses the specific intersections (Di Stefano, 2003).

The Federal Highway Administration (FHWA) proposed guidelines for highway design to increase the safe driving ability of older drivers (Staplin et al., 2001). In this study we examined the effectiveness of the FHWA guidelines in four intersections. We chose to investigate roadway intersections because 45% of all crashes occur at intersections (FHWA, 2004) and because particular characteristics of intersections, such as making tight turns, driving at appropriate speeds, making gap acceptance judgments, and merging into traffic, may be more challenging for older than for younger drivers, thus increasing the risk of crashes and driving errors (Staplin et al., 2001).

We assessed driving performance by recording driving errors as well as by using kinematic data. Kinematic measures, such as lateral and forward acceleration, yaw, and speed, were used to assess driving performance in two previous studies. These kinematic measures were collected by an instrumented car (Classen et al., 2005) and a simulator's computer (Shechtman et al., 2005) and used to assess driving performance.

For kinematic measures to be used as surrogate measures of safe driving performance, they must be well-correlated and/or logically related to accepted safety measures, such as driving errors and/or crashes. For instance, large values of lateral acceleration indicate lane departures and thus suggest reduced driving control, which in turn could infer compromised driving safety. Lane departures may also increase the likelihood of a crash. Further, a lower yaw rate value during the turn would indicate a slower turning rate of the car, which in turn suggests increased time to make the turn and less probability of spinning out of control; thus a lower yaw rate is safer.

Similarly, driving at speeds that are appropriate for the existing road conditions is related to driver's confidence (Godley et al., 2002), which is related to driving safety because rear-end collisions are more likely to occur when driving speeds are too low. In addition, an increased speed during a turn indicates less difficulty in turning and therefore greater driver confidence during turning. Greater forward acceleration may indicate variable speed during the turn; the more a driver slows down, the more he or she would need to speed up again. Driving at a variable speed through an intersection could potentially increase the chance of rear-end collisions.

When plotting the kinematic data during the vehicle's movement through an intersection (Figure 1), one can delineate three distinct phases: approach, turn, and recovery (Classen et al.,

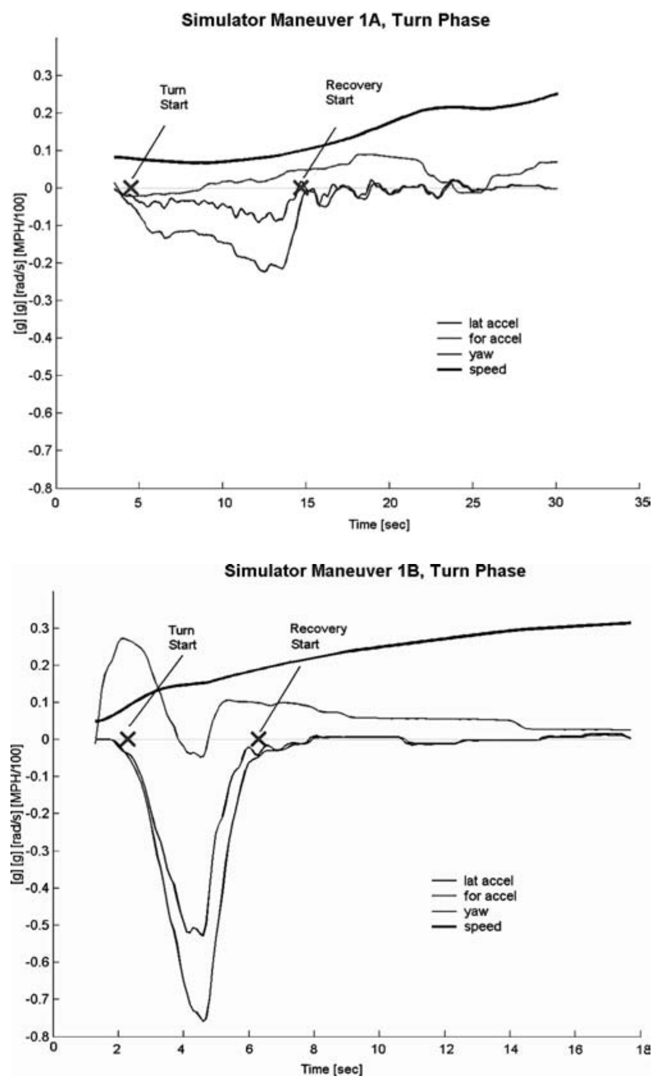

Figure 1 Graphic representation of raw kinematic data (yaw, speed, lateral and forward accelerations) from an individual subject for maneuver 1 (improved intersection—1a vs. unimproved intersection—1b).

2005; Shechtman et al., 2005). These three phases are best determined by a change in yaw, which is defined as the rate of turn of a vehicle expressed in radians per second. As the approach phase ends and the vehicle begins to turn, the value of yaw increases. Thus, in the present study, the beginning of the turn phase/end of the approach phase was operationally defined as the moment in time in which the absolute value of yaw exceeded 0.05 radians/sec. During the turn phase, yaw can reach values of 0.75 radians/sec or more. When the vehicle finishes the turn, yaw decreases to return to a value near zero. Thus, the end of the turn phase/beginning of the recovery phase was operationally defined as the moment in time when the absolute value of yaw fell below 0.05 radians/sec.

During the turn phase, select kinematic measures may be used to infer safe driving performance. The rationale for this is that safe driving performance can be indicated by the driver's control of the vehicle and by the driver's confidence. Control of the vehicle may be expressed by its lateral stability, which is determined by the magnitude of both lateral acceleration (side forces) and yaw. In general, lower lateral forces indicate greater control and stability of the vehicle. Driver confidence may be expressed by higher speeds appropriate for the specific road conditions (Godley et al., 2002). The logic behind this is that when drivers slow down, they can achieve greater lateral control, while not slowing down shows that drivers are confident in controlling their vehicle and thus maintain higher speeds. In addition, slowing down is expected to cause an increase in maximum forward acceleration to bring the vehicle up to the appropriate speed. Thus, stable forward acceleration may also be a sign of driver confidence.

PURPOSE AND HYPOTHESES

The purpose of this study was to investigate the effects of implementing the FHWA guideline (Staplin et al., 2001) on safe driving performance of older (65–85 years) and younger (25–45 years) drivers using a high-fidelity driving simulator. We examined the differences in simulated driving performance of older and younger drivers during the turn phase of four pairs of improved versus unimproved intersections. The improved intersections had the following features: 1) extended receiving lane, 2) right turn with channelization and an acceleration lane, 3) left-turn offset, and 4) separate lane signals with protected left turn phase. The unimproved intersections had similar geometric structure but did not have these enhanced roadway features. Driving performance was inferred from behavioral measures and kinematic measures and was assumed to represent driving safety.

The four intersection pairs are described in detail in the accompanying publication (Classen et al., 2006). They are named maneuvers 1–4 (maneuver 5 was not performed in the simulator). In addition, Table I in the accompanying publication (Classen et al., 2006) describes how we expected the kinematic measures to behave in indicating driving performance through these intersections (only maneuvers 1–4 pertain to the simulator).

We used both behavioral and kinematic measures to indicate safe driving performance. The behavioral measures consisted of driving errors recorded on a standardized form by trained driving evaluators. We hypothesized that fewer driving errors would be made at the improved versus the unimproved intersections and that younger drivers would make fewer driving errors than older drivers. For kinematic measures we used maximal values of yaw, lateral acceleration, speed, and forward acceleration to indicate safe driving performance during the turn phase of these intersection pairs. Our assumptions were that greater lateral control of the vehicle would be expressed by significantly lower values of maximum yaw and lateral acceleration and that greater driver confidence would be expressed by significantly higher speeds and by stable forward acceleration. Based on these assumptions, we hypothesized differences in intersection type in age as follows:

1) All drivers would exhibit greater lateral control of the vehicle and greater driver confidence during the turn phase in the improved versus the unimproved intersections. The basis for this hypothesis is that the improved intersections are more accommodating and provide more forgiving driving conditions than the unimproved intersections. Therefore, we expected enhanced driving performance at these intersections allowing all drivers to have better control of the vehicle and thus to show greater driver confidence.

Table I Summary of both kinematic and behavioral findings

Maneuver #	Maximum yaw (radians/sec)	Maximum lateral acceleration (g)	Maximum speed (mph)	Maximum forward acceleration (g)	Behavioral data
Maneuver 1	I < U	I = U	I = U	I = U	I > U
	Y > O	Y > O	Y > O	Y = O	Y = O
Maneuver 2	I < U	I < U	I = U	I = U	I < U
	Y = O	Y = O	Y = O	Y = O	Y = O
Maneuver 3	I < U	I = U	I = U	I = U	I = U
	Y = O	Y = O	Y = O	Y = O	Y = O
Maneuver 4	I < U	I = U	I = U	I < U	I = U
	Y = O	Y = O	Y = O	Y >O	Y = O
Total (%) improved vs. unimproved	4 (100%)	1 (25%)	0	1 (25%)	2 (50%)
Total (%) old vs. young	1 (25%)	1 (25%)	1 (25%)	1 (25%)	0

I = improved; U = unimproved; Y = young; O = old; = Is equal; > Is significantly greater; < Is significantly smaller; and *In parentheses: approaching significance.

2a) Younger drivers would demonstrate greater driver confidence than older drivers. The basis for this hypothesis is that older drivers tend to decelerate and/or stop at intersections (Staplin et al., 1997), resulting in slower speeds and unstable forward acceleration. Thus, we expect the older drivers to drive at slower speeds, indicating less driver confidence. However, we did not expect the older drivers to display greater forward acceleration because if younger drivers exhibit faster speeds then they are also likely to display greater forward acceleration.

2b) Younger drivers would demonstrate greater lateral forces than older drivers. The hypothesis regarding differences in lateral control between older and younger drivers is more complex. On one hand, older drivers tend to perform more corrections during a turn, which may result in greater lateral forces. On the other hand, we expect younger drivers to negotiate all turns with greater speed and turning at greater speed should produce higher lateral forces as compared to turning at lower speed. In this case, greater lateral forces are the result of the greater speed and not of the lateral instability. Hence, we hypothesize that for the younger drivers, greater lateral forces combined with greater speed are indicative of increased driving confidence and not of reduced lateral stability.

METHODS

Sample

Participants who met our inclusion criteria were recruited from North Central Florida via paid advertisements in newspapers and flyers distributed in the community. The inclusion criteria included: having a valid U.S. driver's license, age (younger group 25–45 years; older group = 65–85 years), mental status (a score of at least 24 on the Mini Mental Status Exam [MMSE] and completing the Trails B test in less than 3 minutes), and vision acuity (20/70 both eyes and 20/40 in one eye in case of blindness in one eye). Exclusion criteria included having seizures within the past year and having major psychiatric or physical disorders affecting functional status. Approval of the research plan was obtained from the University of Florida's Institutional Review Board.

A total of 53 subjects participated in the study, 30 older subjects (73.1 ± 6.3 years of age; 21 males and 9 females) and 23 younger subjects (34 ± 5.9 years of age; 6 males and 17 females). Fourteen of the participants (26%), 4 young (17%) and 10 older (35%), who met all inclusion criteria did not complete the simulated road course evaluation due to experiencing simulator sickness symptoms. We used the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993) to identify subjects who were experiencing simulator sickness symptoms and we discontinued their driving simulation. The occurrence, details, and implications of the simulator sickness in these subjects are discussed in a different manuscript (in preparation).

In the present study we report only on the 39 subjects (74%) who have completed the entire simulator scenario, 19 younger subjects (33.26 ± 5.74 years of age) and 20 older subjects (73.65 ± 5.73 years of age). Unfortunately, the gender distribution in these groups ended up being very uneven: the majority of the younger group was female (15 subjects or 79%) with only 4 males (21%), while the majority in the older group was male (18 subject or 90%) with only 2 females (10%).

Design

The driving performance of older and younger subjects was examined through four pairs of intersections (improved versus unimproved) using kinematic data as well as driving evaluation (behavioral) data. The improved vs. unimproved intersections were replicated in a driving simulator (STI, San Diego). The simulator controls were integrated with an actual vehicle to make the driving experience as realistic as possible. The view of the workstation, vehicle, and visual display can be found in Figure 2. The pairs of intersections (maneuvers) included the presence and absence of the following conditions: (1) an extended receiving lane, (2) a high-speed road with right turn channelization and an acceleration lane at an intersection, (3) an intersection with a left turn offset, (4) a signalized intersection with separate lane signals for each lane and a leading protected left turn signal phase. One of the maneuvers (#2) involved a right turn while the other three maneuvers involved left turns. For specific information regarding the maneuvers, see Table I in the accompanying publication (Classen et al., 2007).

The driving simulator provided visual representations of real intersections located in Gainesville, Florida. Simulator scenarios were created from actual road locations, replicating road geometrics and traffic control devices. The simulated road course consisted of urban, suburban and residential street networks. We designated the improved intersections as "a" and the unimproved intersections as "b." The order of intersections in the simulator scenario was chosen randomly to avoid order effect and was as follows: 1a, 4b, 1b, 3b, 4a, 3a, 2a, 2b. However, the two right turn intersections were put at the end of the simulator scenario because they elicited the most complaints about simulator sickness symptoms from the subjects.

Figure 2 The workstation, vehicle, and projected scenes.

Procedure

The subjects first participated in a phone interview aimed at obtaining demographic information. They then underwent clinical tests to determine their participation eligibility and a standardized road course evaluation. The clinical tests included the MMSE (Folstein & Folstein, 1975), Trails B (Reitan, 1958), and a vision acuity test. On a different day they completed the simulated road course evaluation. The present study addresses the results of the simulated evaluation only.

Prior to "driving" the simulator, participants were screened for simulator sickness using the SSQ (Kennedy et al., 1993). They were then subjected to an acclimation period in the simulator. The acclimation scenario provided a less complex visual representation of the road environment, with progressive increases in complexity. After the acclimation period, participants completed the SSQ again, and those who did not experience simulator sickness symptoms then continue to "drive" the actual simulated road course (the main test scenario), which required approximately 15 minutes to complete. Embedded in this road course were four pairs of test intersections for a total of 8 intersections. The four improved intersections were consistent with the recommendations in the FHWA design guidelines for improving performance and safety of older drivers. The four unimproved intersections did not include these enhancements.

Data Collection

During the simulated driving assessment, both kinematic and behavioral data were collected. The kinematic data collected during the simulated drive were derived from the simulator's computer and reflected the magnitude of forces applied to the car during the simulated road course. Kinematic data included maximum yaw, maximum speed, maximum lateral acceleration, and maximum forward acceleration. The kinematic data were collected at a rate of 60 Hz.

Behavioral data were expressed as errors (yes/no) committed when going through each of the 8 intersections. The measured driving errors for right and left turns included the following: vehicle position, lane maintenance, speed, yielding, signaling, visual scanning, and adjustment to stimuli/traffic signs. In addition, gap acceptance was evaluated for left turns only. The total driving errors per intersection were analyzed. The driving errors were recorded by trained driving evaluators who sat in the car cab and used a standardized road assessment performance sheet as the participant was "driving." The assessment sheet was designed specifically for the simulated road course and followed the order of the simulated intersections.

Three different evaluators collected the data. The interrater reliability among these evaluators was assessed previously in a pilot study using the intra-class correlation (ICC) statistics. In this pilot study, drivers were evaluated on the actual road course by more than one evaluator. The driving evaluators had high reliability correlation coefficients, ranging from $r = 0.80$–1.00. The driving evaluators were blinded to the hypotheses of the study.

Statistical Analysis

The kinematic data were expressed in terms of maximum values of yaw, speed, lateral acceleration, and forward acceleration. These were computed through algorithms using the Matlab software program (Version 7.0.4). The data for each maneuver were analyzed separately using a 2×2 repeated measures ANOVA (SPSS 13.0.1); the within-subject variable was the intersection condition (improved vs. unimproved) and the between-subject variable was age (young vs. old).

Behavioral data were expressed as the cumulative number of errors in each of the intersections and analyzed using non-parametric statistics in SAS. Differences between errors made for the improved vs. unimproved conditions were computed for each subject and these paired data were analyzed separately for each maneuver using the Wilcoxon signed rank tests. To test for the effect of age (young vs. older), the differences in scores were analyzed using the Wilcoxon rank sum test (for independent samples). All comparisons were considered significant at the 0.5 alpha level.

RESULTS

In this section, the kinematic results are addressed per maneuver whereas the behavioral results are addressed collectively. Due to space limitations, only the significant differences are reported. Summary of the findings can be found in Table I. The full results (5 additional tables) can be found on the NODRTC website (http://driving.phhp.ufl.edu/research/projects/5). The graphic representation of an individual driver's raw kinematic data in an improved versus an unimproved intersection is shown in Figure 1.

In maneuver 1 (extended receiving lane) maximum yaw was significantly greater ($F = 7.88$; $p < 0.01$) for the unimproved intersections. No other significant differences were found between the improved and unimproved intersections. There were significant differences between the age groups: maximum yaw ($F = 10.18$; $p \leq 0.01$), maximum lateral acceleration ($F = 8.41$; $p \leq 0.01$), and maximum speed ($F = 5.77$; $p = 0.02$) were all significantly greater for the young subjects as compared to the old subjects. There were no significant differences in forward acceleration.

In maneuver 2 (right turn channelization plus an acceleration lane), maximum yaw ($F = 27.63$; $p \leq 0.01$) and maximum lateral acceleration ($F = 8.92$; $p \leq 0.01$) were significantly greater for the unimproved intersection. There were no differences in forward acceleration and speed between the improved and unimproved intersections. There were no significant differences in kinematic data between the age groups. However, maximum yaw ($F = 3.46$; $p = 0.07$) and maximum lateral acceleration ($F = 2.82$; $p = 0.1$) approached significance with the younger group having greater values.

In maneuver 3 (a left-turn offset), maximum yaw was significantly greater ($F = 47.27$; $p \leq 0.01$) for the unimproved intersection. There were no differences in speed, lateral and forward accelerations between the improved and unimproved intersections. In addition, no significant differences were found between the age groups although maximal speed approached significance ($F = 3.05$; $p = 0.09$), with the young drivers having greater values.

In maneuver 4 (separate lane signals with protected left turn), maximum yaw ($F = 20.89$; $p \leq 0.01$) and maximum forward acceleration ($F = 5.47$; $p = 0.02$) were significantly greater for the unimproved intersection when compared to the improved intersection. Maximum lateral acceleration approached significance ($F = 3.26$; $p = 0.08$), with greater values for the unimproved intersections. There were no differences in maximum speed between improved and unimproved intersections. The only significant differences between age groups were found for maximum forward acceleration ($F = 4.66$; $p = 0.04$), with the older group having greater values. In addition, the interaction (age × intersection) for maximum yaw approaches significance ($F = 3.35$; $p = 0.07$).

The behavioral data indicated significant differences between intersection types in 2 of the 4 maneuvers. In maneuver 1, significantly more driving errors were committed at the improved intersection (coefficient estimate = 65.5; $p = 0.03$). In maneuver 2, significantly more driving errors were committed at the unimproved intersection (coefficient estimate = 96; $p = 0.01$). There were no significant age differences in the number of driving errors committed by younger and older drivers.

To summarize, the differences in intersection type revealed that (1) maximum yaw was significantly greater for all unimproved intersections as compared to their improved counterparts, (2) maximum speed did not differ significantly for any of the intersections, and (3) only one unimproved intersection had significantly greater values of maximum lateral acceleration (maneuver 2) and maximal forward acceleration (maneuver 4) than its improved counterpart. The differences in age group revealed that (1) only one unimproved intersection had significantly greater values of maximum yaw (maneuvers 1) and maximum lateral acceleration (maneuvers 2) than its improved counterpart and (2) only one improved intersection had significantly greater values of speed (maneuvers 1) and forward acceleration (maneuver 2) than its unimproved counterpart. Table I provides a summary of all the statistical findings.

DISCUSSION

Our working hypothesis was that implementing the FHWA guidelines for safe driving at the improved intersections would serve to decrease the lateral forces applied to the car. Maximum yaw and maximum lateral acceleration were assumed to indicate the magnitude of the lateral forces applied to the car during the turn phase in each intersection. Because a decrease in lateral forces would indicate increased lateral stability, we hypothesized that maximum yaw and maximum lateral acceleration would be significantly lower for the improved intersections as compared to the unimproved intersections.

The kinematic data showed that in all four maneuvers, the maximum yaw at the improved intersections was significantly smaller than at the unimproved intersections. Maximum yaw is a measure of the rate of turning of the car around the vertical axis and is indicative of the magnitude of the lateral (side) forces applied to the vehicle when turning. Lateral acceleration is a more direct measure of lateral forces. However, significant differences in lateral acceleration between the improved and unimproved intersections were found for the right turn (maneuver 2).

Yaw and lateral acceleration are highly correlated because their equations have the same variables. Yaw is defined as velocity (v) divided by the radius (r) of the curvature (v/r) while lateral acceleration is defined as velocity squared divided by the radius of the curvature (v^2/r). Since the intersection pairs in the simulated road course were geometrically the same, the radius of the curvature of the turn was identical for the improved and unimproved intersections in each maneuver. Thus, it is curious that in the three left turn maneuvers yaw was significantly different between the improved and unimproved intersections while lateral acceleration was not, especially given that the speed (v) did not differ significantly.

Upon closer examination, lateral acceleration approached significance in maneuver 3 ($p = 0.12$) and maneuver 4 ($p = 0.08$) but not in maneuver 1 ($p = 0.32$). Due to the small sample size, the present study did not have sufficient power, and thus it is possible that increasing the sample size would affect the statistical significance of lateral acceleration. At any rate, yaw proved to be the most sensitive measure of lateral forces for all four maneuvers. Increased lateral forces are indicative of poorer lateral control during the turn when the speed is similar. Thus, the findings of the present study suggest that drivers, regardless of age, exhibited better lateral stability when turning at the improved intersections as compared to the unimproved intersections. Our findings indicate that both older and younger drivers benefited from implementing the FHWA guidelines.

We also hypothesized that implementing the FHWA guidelines would allow drivers to increase their speed when negotiating the improved intersections. We assumed that maximum speed and maximum forward acceleration exhibit the magnitude of forward forces applied on the car and that transversing an intersection at higher speeds indicates greater driver confidence. It was also predicted that negotiating an intersection at higher speeds would cause greater lateral forces to be applied to the car. However, there were no significant differences between the improved and unimproved intersections in any of the maneuvers. Thus, implementing the FHWA guidelines did not appear to affect the driver confidence when negotiating an intersection.

We hypothesized that the young drivers would "drive" with greater confidence and therefore, would negotiate the turns at both improved and unimproved intersections with greater speed than the older drivers. Turning at an intersection with a greater speed would produce higher lateral forces as compared to turning at a lower speed. Therefore, we hypothesized that the younger drivers would exhibit greater lateral forces than older drivers at both improved and unimproved intersections. This may be confusing because in one instance (the improved versus unimproved intersections) we hypothesized that greater lateral forces indicate less lateral stability, yet in the other instance (the young versus old groups) we hypothesized that greater lateral forces indicate greater driving confidence. To clarify, our hypothesis is that greater lateral forces would indicate greater driving confidence only when combined with greater speed, thus indicating that the greater speed (and not the lateral instability) is responsible for the greater lateral forces.

As an example, in maneuver 1 (extended receiving lane), maximum yaw was significantly smaller for the improved intersection (with no significant differences in speed between the intersections), suggesting decreased magnitude of lateral forces and thus increased lateral control when negotiating the turn at the improved intersection. In contrast, the group differences indicated that the young drivers had significantly greater speed as well as significantly greater maximum yaw and maximum lateral acceleration than the older drivers. Therefore, in this case the increase in speed brought about the increase in lateral forces. Thus, the simultaneous increase in speed and lateral forces may suggest greater driving confidence rather than decreased lateral control.

Maneuver 2 was the only right turn in the simulated drive. The road conditions in the improved intersection (right turn channelization and an acceleration lane at the intersection) enhanced the lateral control of both young and old drivers as seen by decreases in maximum yaw and maximum lateral acceleration. As far as age differences are concerned, values approaching significance indicated that the maximum yaw and maximum lateral acceleration were greater for the younger drivers. It is possible that with a larger sample size these values would become significant. The relatively small samples size in this study is partially due to the fact that 33% of the old and 17% of the young participants did not complete the simulated drive because they experienced simulator sickness symptoms.

In Maneuver 3, maximum yaw was smaller for the improved intersection as expected, suggesting that the presence of a left-turn offset, which provides better sight distance and improves gap acceptance judgment, resulted in both younger and older drivers having better lateral control of the vehicle. There were no differences between young and old drivers in any of the kinematic or behavioral measures for this maneuver.

In Maneuver 4, we examined the differences in kinematic data between signalized intersections with and without separate lane signals for each lane and a leading protected left turn phase. According to FHWA guidelines, a protected left turn signal phase is expected to prevent gap acceptance errors. The simulator scenario was programmed so that gap acceptance was tested in the following manner. At the unimproved intersection (without the protected left turn phase) the "drivers" experienced oncoming traffic with one relatively short gap followed by more traffic and eventually a long gap without any oncoming traffic. At the improved intersection, the oncoming traffic was stopped due to the protected left turn signal. Thus, the simulator scenario of the unimproved intersection required a rapid increase in speed in order to successfully drive through the first gap in the oncoming traffic. Indeed, we found significantly greater forward acceleration values for the unimproved as compared to the improved intersection. This is the only maneuver that demonstrated significant differences in forward acceleration.

Forward acceleration and speed do not measure the same construct. Speed can be great in magnitude; yet, if it is constant, forward acceleration will be very small (approaching 0 g). In contrast, forward acceleration is large when the vehicle increases its speed rapidly. It makes sense then that the participants exhibited significantly greater forward acceleration when negotiating the unimproved intersection, because they had to increase their speed rapidly in order to go through the gap successfully. In addition, the lateral forces were greater at the unimproved intersection, signifying reduced lateral control during the turn. It makes sense that the increased forward acceleration would result in greater rate of turn (yaw).

As far as age differences in Maneuver 4, we found that the older participants had significantly greater forward acceleration than the younger group, which may indicate a "panicked" attempt to successfully drive through the gap in the oncoming traffic. There is another indication that the older drivers were "gunning it" more than the young drivers in an attempt to successfully make it through the gap in oncoming traffic. The interaction (age $\times$ intersection) for maximum yaw approached significance ($p = 0.07$), showing no differences between young and old drivers in the improved intersection, but greater maximum yaw for the young group in the unimproved intersection. Again, it is possible that with a greater sample size this interaction value would become significant.

The behavioral data indicated no significant differences in driving errors between older and younger subjects. However, there were differences in driving errors between the improved and unimproved intersections in two of the maneuvers. The difference in the number of driving errors in maneuver 2 was in the expected direction, with subjects committing fewer errors in the improved intersection (right turn channelization with an acceleration lane). In maneuver 1, however, the results were unexpected, as the subjects committed more errors in the improved intersection (a left turn with an extended receiving lane). A possible explanation has to do with handling of the car. There was too much "play" in the steering wheel of the car, which affected the driving performance during recovery from the turn. The wider turn in the improved intersection (due to the extended receiving lane) required more side to side corrections before returning the steering wheel to neutral. Indeed, an in depth inspection of the behavioral data showed that the majority (65%) of the driving errors in the improved intersection of maneuver 1 were lane maintenance errors during the recovery phase. Therefore, it is not surprising that fewer errors were made when negotiating the unimproved intersection.

The limitations of the study include a small sample size and an uneven gender distribution between the age groups. In addition, the presence of simulator sickness symptoms in some participants may have biased the results of the study because the data from participants who experienced these symptoms were not analyzed. Lastly, there is a possibility that the simulator may not realistically emulate the real world. Specifically, some participants companied that there was too much “play” in the steering wheel of the car cab. Also, driving simulators have not yet been validated as reliable predictors of on-road driving performance. The present study only begins to scratch the surface regarding the effectiveness of the FHWA guidelines. Future studies need to address additional guidelines (only four of the guidelines were tested in the present study) and additional kinematic measures to provide more complete information on driving performance. These measures may include time to achieve maximal values of speed, yaw, and acceleration, the car’s position with respect to the roadway dividing line, steering wheel angle input, brake actuation, and collisions with other vehicles and pedestrians.

CONCLUSIONS

The kinematic findings of the present study suggested that the FHWA guidelines for implementing safe road conditions may be helpful for both younger and older drivers in the specific roadways tested in this study. Overall it seemed that both younger and older drivers could benefit from roadways with these safety features as indicated by the increased lateral control of the vehicle when negotiating the turn phase of these intersections. Thus, the findings of the present study may generate critical information for those involved in the design of roadway systems, such as engineers, planners, and policy-makers, to enhance safe driving. Most notably, in all four tested intersection pairs, implementing the guidelines brought about an increase in driving safety as indicated by decreased maximal yaw. A lower rate of yaw during a turn is safer because it indicates a slower turning rate of the car, which in turn suggests increased time to make the turn and thus less probability of spinning out of control during the turn. However, these findings need to be interpreted with caution due to the limitations of the study.

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