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

Preliminary Results

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The Federal Highway Administration proposed guidelines for highway design to increase the safe-driving ability of older drivers; however, little empirical evidence exists to support these guidelines. This study investigated the effects of *improved* versus *unimproved* intersections, using a high-fidelity driving simulator. Kinematics measures and behavioral evaluations were obtained to determine whether driving performance during negotiation of *improved* intersections was safer for older (65–85 years) and younger (25–45) drivers. Five pairs of intersections were compared. Three of the 5 comparisons indicated significantly greater lateral control stability (as measured by maximum yaw rate) during turns at the *improved* intersections. This preliminary report is based on data from 19 subjects (5 young and 14 older adults). Despite the small sample size, the findings of this study suggest that some of the Federal Highway Administration guidelines for implementing safe road conditions are helpful in defining intersection characteristics that could lead to safer driving by both older and younger adults. These results may yield critical information for engineers, planners, policymakers, and others involved in the design of roadway systems to enhance safe driving. **Key words:** *driving kinematics*, *driving simulation*, *highway safety*, *intersection design*, *older and younger drivers*, *roadway infrastructure*

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OLDER ADULTS comprise the fastest growing segment of the American population. This group is living longer and therefore driving longer.[1] Older adults may be at an increasing risk for unsafe driving behaviors and crashes due to sensory and motor age-related changes, greater likelihood of multiple, chronic diseases, and increased medication use.[2,3] In addition, certain roadway intersection characteristics may be more problematic for older drivers, thereby increasing the risk of driving errors and crashes. 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 these guidelines.[4]

Clinical measures have not predicted on-road driving performance reliably, making identification of at-risk drivers difficult.[5,6] Although not fully validated, driving simulators provide a viable alternative to on-the-road evaluations. As computer and display technologies have improved, driving simulators are becoming more commonly employed for screening drivers as well as for remediation and research purposes. Some advantages of driving simulators are that they provide greater control of environmental and experimental variables than can be obtained on the road or even on a test track facility and that they are safer than the on-road evaluation.[7] Implementation of realistic representation of road geometrics and traffic control devices in a virtual reality system requires a wide field of view and a high image resolution. It also requires integrated visual, auditory, and kinematics feedback to the "driver." This feedback allows the "driver" to control the vehicle through steering, accelerating, and braking.[8]

On the basis of on-road and simulation studies, as well as previous crash and observational data,[9–12] we expect the improved intersections to produce safer driving for all drivers, but with greater benefits for the older drivers. In particular, we expect the kinematics data during turning at the improved intersections to show greater lateral control stability (as indicated by lesser lateral forces) and greater forward motion (as indicated by increased speed).

PURPOSE

Using the proposed FHWA guidelines for highway design to increase the safe-driving ability of older drivers, we replicated *improved* versus *unimproved* roadway conditions in a driving simulator. We examined the turn phase of these intersections to determine whether turning at improved intersections is safer for both older (65–85 years) and younger (25–45 years) drivers. To discern this, we utilized kinematics measures obtained from a high-fidelity simulator (with a wide field-of-view and advanced vehicle dynamics) in conjunction with behavioral evaluations obtained by trained driving evaluators.

METHODS

Sample

Participants who met our inclusion criteria were recruited from North Central Florida via paid advertisements in newspapers and via flyers distributed to aging service centers (eg, Area Agency on Aging), apartment complexes and community centers. Participants were also recruited via open houses held at the University of Florida's Gator-Tech Smart House, and from word-of-mouth referrals. Approval was obtained from the University of Florida's institutional review board, and all participants completed a telephone consent and informed consent before enrolling in the study.

Design

The driving performance of old and young subjects through 5 pairs of intersections (improved vs unimproved) was examined using kinematics data as well as driving-evaluation (behavioral) data. The *improved* versus *unimproved* roadway conditions were replicated in the driving simulator (STI, San Diego, Calif). The simulator controls were integrated with an actual vehicle to make the driving experience as realistic as possible.

The pairs of intersections (maneuvers) included the presence and the absence of the following conditions: (1) an extended receiving lane, (2) high-speed roads with right-turn channelization and an acceleration lane at an intersection, (3) intersections with left-turn offsets, (4) signalized intersections with separate lane signals for each lane and leading protected left-turn signal phases, and (5) signalized intersections with overhead lane-use signs supplemented with pavement markings. One of the maneuvers (#2) involved a right turn whereas the other 4 maneuvers involved left turns.

Procedure

This study was conducted in a driving simulator, which provided visual representations of real intersections located in Gainesville, Fla. 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. An example of a simulated scene, as seen by a driver sitting in the vehicle, can be found in Figure 1. The view of the workstation, vehicle, and visual display can be found in Figure 2.

Prior to "driving" the simulator, participants were screened for simulator sickness. 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 actual simulated road course (the main test scenario), which required approximately 15 minutes of "driving." Embedded in the road course were 5 pairs of test intersections for a total of 10 intersections. The 5 *improved* intersections were consistent with the recommendations in the FHWA design guidelines for improving performance and safety of older drivers. The 5 *unimproved* intersections did not include the enhancements proposed in the FHWA design guidelines.

Data collection

Prior to testing in the simulator, participants engaged in a telephone interview and a brief clinical assessment. During the simulator driving assessment, both kinematics and behavioral data were collected. The methods used to obtain data were similar to those employed in a parallel study conducted on those actual roadways.[13]

The kinematics data included maximum yaw, maximum speed, maximum lateral, and forward acceleration, as well as the combined acceleration (the resultant acceleration

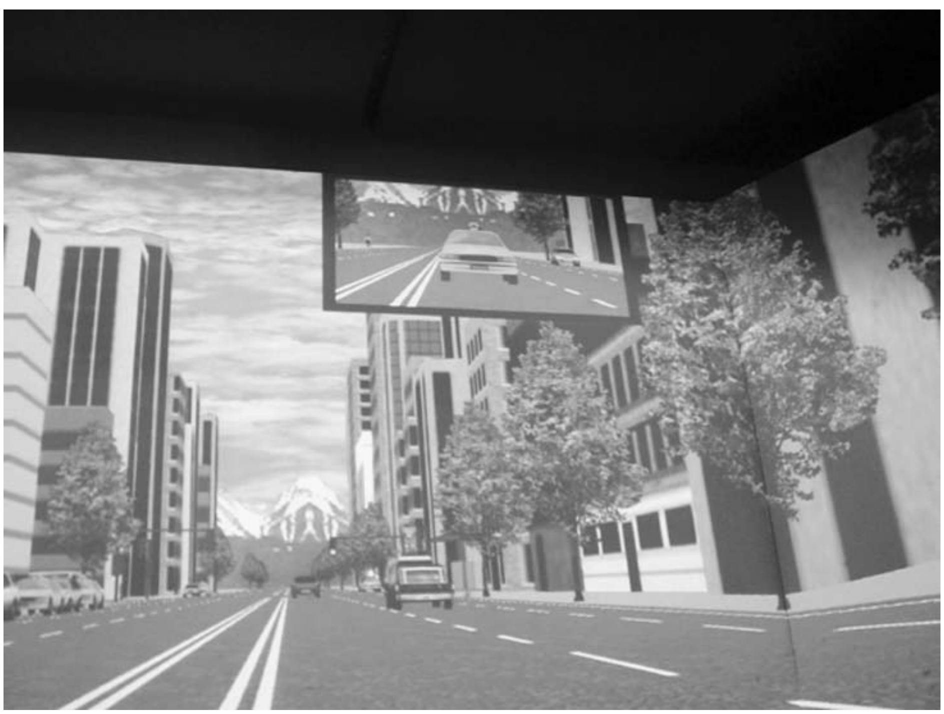

Figure 1. The "driver's view" of the forward and rear scenes in the driving simulator.

Figure 2. The workstation overlooks the driver, vehicle, and projected scenes in the driving simulator.

magnitude of both lateral and longitudinal accelerations). The kinematics data were collected at a rate of 60 Hz. Additional measures and traffic conditions that were automatically recorded during trials included elapsed time from the beginning of run, total distance traveled from the beginning of the run, lateral lane position with respect to the roadway dividing line, vehicle heading angle (degrees), steering wheel angle input, brake actuation, driver signalizing, status of traffic signals, other roadway traffic, and collisions with other vehicles and pedestrians.

Behavioral data measured driving behaviors and were expressed as errors (yes/no) committed when going through each of the 10 intersections. The measured driving errors included the following: vehicle position, lane maintenance, speed, yielding, signaling, visual scanning, adjustment to stimuli/traffic signs, and gap acceptance (left turns only). The behavioral data consisted of total driving errors obtained by trained driving evaluators who sat in the car cab, using a standardized road performance sheet, as the participant was "driving." Some of the participants (28%) who met all inclusion criteria did not complete the simulated road course evaluation because they experienced simulator sickness symptoms.[14]

DATA ANALYSES

A power analysis with $\alpha = .05$ and $\beta = .80$ with a moderate effect size and attrition rate of 20% yielded a requirement of 109 subjects. In this preliminary analysis, only 19 subjects had completed the simulated course.

Kinematics data were computed through algorithms, using *Matlab* [computer program] (Version 7.0.4, MathWorks, Inc, 1984–2005). Behavioral data were entered and managed in an MS-Access database. All data were then imported to MS-Excel and analyzed using *SPSS for Windows* [computer program] (Version 13.0.1, SPSS Inc, Chicago, 2005) and *SAS (r)* [computer program] (Version 9, SAS Institute Inc, Cary, NC, 1999).

The kinematics data were expressed in terms of maximum values for measures selected to best reflect intersection turn phase performance. These included yaw, speed, and lateral, longitudinal, and combined accelerations. The data for each maneuver were analyzed separately, using a 2 × 2 repeated measures ANOVA; 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 5 maneuvers. Differences between errors made for the *improved* versus *unimproved* conditions were computed for each subject. The paired data for each maneuver were analyzed separately, using Wilcoxon signed rank tests. To test for the effect of age (young vs old), the difference scores were analyzed using Wilcoxon rank sum test.

RESULTS

The kinematics data for maneuver 1 (Table 1) showed no significant differences between the improved intersection with the extended receiving lane and the unimproved intersection for either age group. There were also no significant differences between the age groups. The behavioral data (Table 6) indicated that significantly more driving errors were made at the improved intersection than at the unimproved intersection (Wilcoxon = 28; $P = .011$). However, there were no significant differences in driving errors between the age groups.

The kinematics data for maneuver 2 (Table 2) revealed that maximum yaw was significantly less at the improved intersection (right turn with channelization and an acceleration lane) than at the unimproved intersection ($F = 6.53$; $P = .02$). No significant

Table 1. Kinematics data of younger and older drivers during the turn phase of maneuver 1; $n = 19$ ($n_{\text{young}} = 5$, $n_{\text{old}} = 14$)

		Combined maximum acceleration (g)		Maximum longitudinal acceleration (g)		Maximum lateral acceleration (g)		Maximum yaw (radians/second)		Maximum speed (m/h)	
		Descriptive statistics									
Intersection	**Age**	***M***	**SD**	***M***	**SD**	***M***	**SD**	***M***	**SD**	***M***	**SD**
Improved	Young	0.252	0.092	0.150	0.074	0.233	0.108	0.996	0.304	13.741	3.332
	Old	0.180	0.075	0.157	0.075	0.128	0.050	0.704	0.156	11.657	2.312
Unimproved	Young	0.222	0.191	0.109	0.096	0.204	0.191	1.118	0.690	12.005	4.087
	Old	0.210	0.080	0.158	0.078	0.160	0.061	0.933	0.229	12.633	2.450
		Inferential statistics									
		F	***P***	***F***	***P***	***F***	***P***	***F***	***P***	***F***	***P***
Age group (older vs younger drivers)		1.010	.329	0.840	.372	3.347	.085	3.135	.095	0.353	.560
Intersection type (improved vs unimproved)		0.001	.995	0.512	.484	0.009	.925	3.886	.065	0.257	.618
Interaction (Age × Intersection)		0.947	.344	0.584	.455	1.721	.207	0.358	.557	3.273	.088

*$P \leq .05$.

Table 2. Kinematics data of younger and older drivers during the turn phase of maneuver 2; $n = 19$ ($n_{young} = 5$, $n_{old} = 14$)

		Combined maximum acceleration (g)		Maximum longitudinal acceleration (g)		Maximum lateral acceleration (g)		Maximum yaw (radians/second)		Maximum speed (m/h)	
Descriptive statistics											
Intersection	**Age**	***M***	**SD**	***M***	**SD**	***M***	**SD**	***M***	**SD**	***M***	**SD**
Improved	Young	0.213	0.100	0.121	0.096	0.195	0.091	1.239	0.319	13.391	7.013
	Old	0.228	0.095	0.191	0.084	0.173	0.093	1.085	0.338	12.321	2.689
Unimproved	Young	0.247	0.088	0.157	0.100	0.242	0.093	1.451	0.309	12.042	1.353
	Old	0.224	0.084	0.188	0.079	0.171	0.075	1.190	0.315	11.628	3.761
Inferential statistics											
		F	***P***	***F***	***P***	***F***	***P***	***F***	***P***	***F***	***P***
Age group (older vs younger drivers)		0.006	.941	1.534	.232	1.260	.277	1.745	.204	0.189	.669
Intersection type (improved vs unimproved)		0.646	.433	0.799	.384	1.471	.242	6.528	.020*	1.114	.306
Interaction (Age × Intersection)		1.042	.322	1.121	.305	1.718	.207	0.734	.404	0.115	.739

*$P \leq .05$.

differences in kinematics data were found between the age groups. The behavioral data did not show differences in driving errors between the improved intersection and the unimproved intersection or between the age groups (Table 6).

The kinematics data for maneuver 3 (Table 3) indicated that maximum yaw was significantly less at the improved intersection with the left-turn offset than at the unimproved intersections ($F = 12.84$; $P = .002$). No significant differences in kinematics data were found between the age groups. The behavioral data showed no significant differences in driving errors between the improved intersection and unimproved intersection or between the age groups (Table 6).

The kinematics data for maneuver 4 (Table 4) showed that both maximum yaw ($F = 13.74$; $P = .002$) and maximum longitudinal acceleration ($F = 9.15$; $P = .008$) were significantly smaller for the improved intersection (a signal intersection with separate lane signals for each lane with a leading protected left-turn phase) than for the unimproved intersection. No significant differences in kinematics measures were found between the age groups. The behavioral data indicated no significant differences in driving errors between improved and unimproved intersections or between the age groups (Table 6).

The kinematics data for maneuver 5 (Table 5) revealed no significant differences between improved intersection (overhead lane-use signs supplemented by enhanced pavement markings) and unimproved intersection. No significant differences in kinematics were found between age groups. The behavioral data did not show significant differences in driving errors between improved intersection and unimproved intersection or between the age groups (Table 6). The total

Table 3. Kinematics data of younger and older drivers during the turn phase of maneuver 3; $n = 19$ ($n_{young} = 5$, $n_{old} = 14$)

		Combined maximum acceleration (g)		Maximum longitudinal acceleration (g)		Maximum lateral acceleration (g)		Maximum yaw (radians/second)		Maximum speed (m/h)	
Descriptive statistics											
Intersection	**Age**	***M***	**SD**	***M***	**SD**	***M***	**SD**	***M***	**SD**	***M***	**SD**
Improved	Young	0.231	0.146	0.123	0.105	0.225	0.144	0.978	0.382	14.040	4.746
	Old	0.241	0.135	0.194	0.122	0.194	0.092	0.907	0.277	13.448	4.014
Unimproved	Young	0.222	0.103	0.108	0.084	0.219	0.102	1.280	0.525	12.866	4.445
	Old	0.272	0.140	0.193	0.066	0.200	0.075	1.116	0.305	14.073	4.419
Inferential statistics											
		F	***P***	***F***	***P***	***F***	***P***	***F***	***P***	***F***	***P***
Age group (older vs younger drivers)		0.250	.623	3.134	.095	0.333	.571	0.532	.476	0.020	.889
Intersection type (improved vs unimproved)		0.085	.775	0.098	.758	0.001	.987	12.842	.002*	0.201	.660
Interaction (Age × Intersection)		0.293	.595	0.069	.796	0.051	.824	0.428	.522	2.150	.161

*$P \leq .05$.

Table 4. Kinematics data of younger and older drivers during the turn phase of maneuver 4; $n = 19$ ($n_{young} = 5$, $n_{old} = 14$)

		Combined maximum acceleration (g)		Maximum longitudinal acceleration (g)		Maximum lateral acceleration (g)		Maximum yaw (radians/second)		Maximum speed (m/h)	
Descriptive statistics											
Intersection	**Age**	***M***	**SD**	***M***	**SD**	***M***	**SD**	***M***	**SD**	***M***	**SD**
Improved	Young	0.226	0.137	0.092	0.056	0.188	0.111	0.977	0.371	12.713	4.350
	Old	0.227	0.136	0.156	0.097	0.174	0.089	0.965	0.288	11.622	3.178
Unimproved	Young	0.276	0.183	0.195	0.138	0.261	0.184	1.413	0.687	13.490	6.100
	Old	0.2660	0.126	0.211	0.080	0.206	0.119	1.172	0.504	13.150	3.760
Inferential statistics											
		F	***P***	***F***	***P***	***F***	***P***	***F***	***P***	***F***	***P***
Age group (older vs younger drivers)		0.003	.954	0.846	.370	0.417	.527	0.371	.550	0.163	.691
Intersection type (improved vs unimproved)		2.648	.122	13.740	.002*	3.168	.093	9.153	.008*	1.128	.303
Interaction (Age × Intersection)		0.037	.849	1.245	.280	0.478	.499	1.167	.295	0.120	.734

*$P \leq .05$.

Table 5. Kinematics data of younger and older drivers during the turn phase of maneuver 5; $n = 19$ ($n_{young} = 5$, $n_{old} = 14$)

		Combined maximum acceleration (g)		Maximum longitudinal acceleration (g)		Maximum lateral acceleration (g)		Maximum yaw (radians/second)		Maximum speed (m/h)	
Descriptive statistics											
Intersection	**Age**	***M***	**SD**	***M***	**SD**	***M***	**SD**	***M***	**SD**	***M***	**SD**
Improved	Young	0.171	0.080	0.109	0.070	0.164	0.081	0.867	0.250	12.155	3.561
	Old	0.200	0.103	0.158	0.099	0.168	0.089	0.863	0.234	12.850	3.255
Unimproved	Young	0.193	0.122	0.086	0.051	0.187	0.121	0.944	0.342	12.365	3.560
	Old	0.195	0.130	0.130	0.086	0.153	0.087	0.837	0.246	12.438	2.789
Inferential statistics											
		F	***P***	***F***	***P***	***F***	***P***	***F***	***P***	***F***	***P***
Age group (older vs younger drivers)		0.072	.791	1.296	.271	0.101	.755	0.187	.671	0.059	.810
Intersection type (improved vs unimproved)		0.195	.665	1.991	.176	0.108	.746	0.458	.507	0.044	.837
Interaction (Age × Intersection)		0.465	.505	0.024	.878	2.309	.147	1.918	.184	0.417	.527

number of errors (the sum of driving errors in all 5 maneuvers) was significantly greater for the improved intersection than for the unimproved intersection (Wilcoxon = 40.5; $P = .035$).

DISCUSSION

The kinematics data showed significant differences in maximum yaw between improved intersection and unimproved

Table 6. Behavioral data reflecting driving errors of younger and older drivers during turn phase in a driving simulator for 5 maneuvers $n = 19$ ($n_{young} = 5$, $n_{old} = 14$)*

		Maneuver 1		Maneuver 2		Maneuver 3		Maneuver 4		Maneuver 5		All Maneuvers	
Descriptive statistics													
Intersection	**Age**	***M***	**SD**	***M***	**SD**	***M***	**SD**	***M***	**SD**	***M***	**SD**	***M***	**SD**
Improved	Young	0.833	0.983	0.500	0.548	1.500	1.761	1.000	1.673	0.667	1.211	4.500	3.937
	Old	2.000	1.414	0.357	0.842	1.071	1.542	1.214	1.122	0.786	0.975	5.429	3.956
Unimproved	Young	0.500	0.837	0.833	0.408	1.000	0.894	0.167	0.408	0.667	1.633	3.167	2.041
	Old	0.929	1.207	0.714	0.611	1.143	1.351	1.214	1.311	0.500	0.760	4.500	4.109
All errors	Improved	1.650	1.387	0.400	0.754	1.200	1.576	1.150	1.268	0.750	1.020	5.150	3.870
	Unimproved	0.800	1.105	0.750	0.550	1.100	1.210	0.900	1.210	0.550	1.050	4.100	3.611
Inferential statistics													
		W	***P***	***W***	***P***	***W***	***P***	***W***	***P***	***W***	***P***	***W***	***P***
Age group		75.5	.309	60	.819	55	.528	53	.410	69	.613	59.5	.805
Intersection type		−28	.011†	14	.121	−4	.823	−8.50	.406	−7.50	.344	−40.5	.035†

*W indicates Wilcoxon statistic.
†$P \leq .05$.

intersection in 3 of the 5 maneuvers (maneuvers 2, 3, and 4). In these maneuvers, the maximum yaw was significantly smaller at the improved intersections than at the unimproved intersections. Maximum yaw indicates the magnitude of the lateral (side) forces applied when turning. Increased side forces are indicative of poorer lateral control during the turn. Thus, the findings of this study suggested that drivers, regardless of age, exhibited better lateral stability when turning at the improved intersections than when turning at the unimproved intersections.

The behavioral data indicated that less overall driving errors were made in the unimproved intersections than in the improved intersections. These findings were unexpected. One possible explanation may be related to the increased amount of simulated visual stimuli that the participants had to process while negotiating the turn in the improved intersections due to their enhanced features. The increased visual input in the simulated environment may be more taxing from a behavioral standpoint, causing an increase in the amount of driving errors. In addition, our findings indicated that there were no differences in driving errors or in kinematics between the age groups.

The kinematics findings of this study suggested that the FHWA guidelines for implementing safe road conditions may be helpful for both younger and older drivers at 3 of the 5 improved intersections. Overall, it seemed that both young and older drivers may benefit from roadways with these safety features. Thus, the findings of this study may generate critical information for those involved in the design of roadway systems, such as engineers, planners, and policymakers, to enhance safe driving. However, these findings need to be interpreted with caution because of the small sample size and the possibility that the simulator may not realistically emulate the real world.

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