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

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Objective. *To test the effectiveness of the FHWA guidelines for intersection design.*

Methods. *In an experimental design we used kinematics measures from an instrumented vehicle and behavioral (error) data collected during on-road evaluations to quantify the effects of* improved *versus* unimproved *intersections (turn phase) and to determine if these intersections were safer (vehicular stability and driver confidence) for both older (65–85 years) and younger (25–45) drivers. We analyzed kinematics data with a 2 × 2 repeated measures ANOVA and behavioral data (driving errors yes, no) with Wilcoxon sign rank test (within subject variable: intersection improved vs. unimproved) and Wilcoxon rank sum test (between subject variable: age, younger vs. older driver).*

Results. *Kinematics measures (turn phase), showed three maneuvers had statistically significantly lesser side forces (measured by lateral acceleration and combined acceleration) for the improved conditions, and four maneuvers had statistically significantly greater, yet appropriate, speeds for the improved conditions. Lesser side forces indicated improved lateral stability and increased speed indicated greater confidence. Drivers made fewer errors on two of the improved intersections; but across all maneuvers, older drivers appeared to make fewer errors on the improved intersections.*

Conclusions. *This study brings empirical intersection design and safety information for engineers and city planners to consider as they plan and develop intersections. Future researchers may want to use the conceptual and analytical framework of this study to determine the effectiveness of other FHWA guidelines. Given that these intersection design guidelines benefit younger and older drivers alike, plausible policy-making opportunities are opened in the design of safe roadway systems, to benefit the broad spectrum of adult drivers.*

Keywords Experimental Design; Older Drivers; On-the-Road Evaluation; Instrumented Vehicle; Roadway Infrastructure; Improved Intersections; Policy Implications

BACKGROUND

The older population is livinglonger and driving longer (Centers for Disease Control and Prevention, 2002), but age-related changes and an increased likelihood of multiple chronic diseases and medication use put this group at an increased risk for unsafe driving behaviors and crashes (Dellinger, Langlois, & Li, 2002; Eberhard, 1996). In fact, national statistics indicate that after teenage drivers, this group has the second highest fatality rates from crashes.

The older driver group is, due to frailty and fragility, at a higher risk than any other adult driver group for injuries (NHTSA, 2006). The FHWA (2004) reported that 45% of all road crashes occur at intersections, with 56% of these occurring in urban areas. Clinical measures have not been reliable predictors of on-road driving performance, thus making identification

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of at-risk drivers difficult (Insurance Institute for Highway Safety [IIHS], 2003; McGwin et al., 2000). Additionally, certain roadway intersection characteristics may be more problematic for older drivers, thereby further 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 (Staplin et al., 2001). These guidelines included assessments and recommendations applicable to four categories of roadway design features: those appropriate for intersections, interchanges, roadway curvature/passing zones, and construction work zones. This study dealt exclusively with roadway intersection features in an urbanized area because this is where crashes are most prevalent.

Measures of Safe Driving Performance

The most commonly accepted measures of road safety are crash rates based on the numbers of fatalities, injuries, and property damage relative to the size of driver population groups, miles driven, or time of driving. When a particular road feature is widespread it becomes possible to conduct global safety evaluations using crash rates. However, crash-related measures are either impossible or impractical to use when evaluating the safety consequences of specific road features or driver characteristics. Such evaluations require the use of surrogates that have either been shown to correlate highly with crash rates or are logically related to crashes. For example, we can infer safety from the number of lane departures or by recording the extreme lateral deviations or highly variable control performances. Likewise, driver's confidence, another surrogate for safety, is related to assuming a speed appropriate for the road condition (Godley et al., 2002). If the speed produced is too low, rear-end collisions are more likely to occur, or if it is too high the driver may loose control of the vehicle. Thus, kinematics measures such as longitudinal and lateral accelerations, combined (longitudinal and lateral) acceleration, yaw, and speed can be used to determine safe driving performance.

Measures During the Turn Phase of Intersections

Intersection maneuvers can be delineated into three segments or phases: approach, turn, and recovery. The beginning of the turn phase, in this article, is operationally defined as a threshold value of 0.05 radians/sec. During a turn yaw can reach a value as great as 0.75 radians/sec, or during a very extreme turning maneuver, even more. The end of the turn phase and the beginning of the recovery phase is defined as yaw dropping to a value of 0.05 radians/sec. During the turn phase of an intersection safe driving performance can be observed by a steady vehicular state and driver confidence. The steady vehicular state is expressed as lateral stability of the vehicle that can be determined by measuring lateral acceleration (side [g] forces) and the magnitude of yaw (rate of turn measured in radians/sec). In this analysis these measures are the extreme values (maximum acceleration and yaw). Lateral acceleration and yaw are functionally related and greater values in each of these generally indicate lesser lateral vehicular stability. Lateral acceleration and longitudinal acceleration are not truly independent because when drivers slow down, greater lateral control can be achieved, yet an increase in maximum longitudinal acceleration is expected to bring the vehicle up to speed, thus making it necessary to also consider combined acceleration as a measure of control during turns. Maximum longitudinal acceleration is expected not to be greater or lesser but to stay the same through the improved (more forgiving and more accommodating) intersections. Driver confidence is expressed as greater speed appropriate for the road condition and stable maximum longitudinal acceleration across maneuvers.

Intersections and Expectation for Driving Performance by Type and Age Group

Using the FHWA guidelines for improved driving performance (vehicle stability and driver confidence), we describe next five intersection pairs (extended receiving lane, right turn with channelization, separate lane signals with protected left turn (PLT) phase, left turn offset, and no acute turn angle) used in this study. Table I provides a summary illustration of the five intersections discussed below. In this table we explain the corresponding FHWA guideline contained in the report (Staplin et al., 2001) as it pertains to each intersection type and state the salient characteristics of the improved intersections. We also outlined the intended affects of each of the improved intersections on driving performance and included the expected differences in performances for these intersections. *The Road Course and Maneuver Locations*, describing the guidelines, can be obtained from the National Older Driver Research and Training Center (NODRTC) web site at: http://driving.phhp.ufl.edu/research/projects/4.

Maneuver 1: Extended Receiving Lane—The extended receiving lane provides more turning space and allows the driver to make wider turns without running off the road. This larger radius turn should decrease the lateral forces applied to the vehicle (lateral acceleration and yaw), thus allowing the turn phase to be driven with more confidence, as expressed by maintaining higher speeds. The expected safety outcomes are: fewer lane maintenance errors (including decreased run-off-road incidents and encroachment errors) and reduced rear-end collisions (due to less variable and higher speeds). The unimproved intersection has a tighter turn, which requires drivers to reduce speed, unless they can increase the muscular effort of turning the wheel. Negotiating tighter turns may therefore be more difficult for older drivers resulting in less rotation of the steering wheel (McKnight & Steward, 1990) and causing greater lateral forces and positional errors during the turn. This would require more corrections, resulting in lower lateral stability and lower speed. In addition, slowing down more to make the tighter turn would require greater forward acceleration to get up to the appropriate speed. Thus, greater forward acceleration is expected in the unimproved intersection (Campbell, 1993; Council & Zeeger, 1992; FARS, 1998; IIHS, 2000; Staplin & Lyles, 1991).

Maneuver 2: Right Turn with Channelization and Acceleration Lane—The right turn channelization combined with an acceleration lane serves the function of permitting drivers to

Table I Description of the improved intersections and the expected outcomes

Improved intersection type	Definition (FHWA recommendations, Staplin et al., 2001)	Improvement	Expected safety outcomes	Expected kinematics outcomes
Maneuver 1: Extended Receiving lane	"A minimum receiving lane width of 3.6 m (12 ft) is recommended, accompanied, wherever practical, by a shoulder of 1.2 m (4 ft) minimum width."	Allows a vehicle to make wider turns without running off the road or into another lane	Reduced run-off-road incidents and encroachment errors; decreased rear-end collisions due to maintaining higher speed	Greater lateral stability (smaller yaw and lateral acceleration), higher and less variable speed (lesser forward acceleration)
Maneuver 2: Right turn with channelization and acceleration lane	"If right-turn channelization is present at an intersection, an acceleration lane providing for the acceleration characteristics of passenger cars as delineated in AASHTO specifications (1994) is recommended."	The right-turn channelization gives the turning vehicle protection from approaching vehicles, the acceleration lane allows minimal speed reduction	Reduced collisions at the intersection; reduced rear-end collisions due to better matching of speeds with approaching vehicles	Greater lateral stability (smaller yaw and lateral acceleration), achieving higher speeds more quickly, no difference in forward acceleration
Maneuver 3: Left turn offset	"... unrestricted sight distances and corresponding left-turn lane offsets are recommended whenever possible in the design of opposite left-turn lanes at intersections."	Provides improved sight distance (enhanced vision of opposing traffic) during green-ball signal phase and better gap acceptance judgments	Reduced collisions at intersections due to decreased dangerous short gap acceptance; reduced rear-end collisions due to long queues of traffic in turn lane	Greater lateral stability (smaller yaw and lateral acceleration), greater speed, no difference in forward acceleration
Maneuver 4: Separate lane signals with protected left turn (PLT) phase	"To reduce confusion during an intersection approach, the use of a separate signal to control movements in each lane of traffic is recommended... a leading protected left-turn phase is recommended..."	Serves to eliminate the need for gap acceptance judgments (driver's decision of when to turn)	Reduced collisions at intersection and increased traffic flow due to reduced queue length and wait time	Greater lateral stability (smaller yaw and lateral acceleration), greater speed, lesser forward acceleration
Maneuver 5: Standard intersection with roadways intersecting at 90 degrees	"In the design of new facilities where right-of-way is not restricted, all intersecting roadways should meet at a 90-degree angle. in the design of new facilities or redesign of existing facilities where right-of-way is restricted, intersecting roadways should meet at an angle of not less than 75 degrees."	The 90-degree intersection allows for increased lateral stability and speed control while negotiating the intersection	Reduced run-off-road incidences due to greater lateral control and reduced rear-end collisions due to improved speed control	Compared to the degraded intersection design we expect increased lateral stability (smaller yaw and lateral acceleration), and speed

merge into the intersecting road safely by reducing the differences in speed between the merging and approaching vehicles (Staplin et al., 1997). Channelization allows for a more gradual turn, which is expected to generate lower lateral forces (maximal yaw and lateral acceleration) and thus allow drivers to drive at higher speeds. In addition, the acceleration lane allows the drivers to achieve higher speeds more quickly, to better match the speed of the approaching vehicle. Forward acceleration is not expected to differ between the improved and unimproved intersection, because a different feature in each intersection is expected to produce greater forward acceleration, thus equalizing the difference. The improved intersection should display greater forward acceleration due to allowing a driver to achieve higher speed, while the unimproved intersection is expected to display greater forward acceleration due to a more variable speed (slowing down in order to merge and then having to speed up to achieve the appropriate speed for the road conditions) (Campbell, 1993; Council & Zeeger, 1992; FARS, 1998; IIHS, 2000; Staplin & Lyles, 1991).

Maneuver 3: Left Turn Offset—This feature is proposed to increase the sight distance of drivers and improve driver's judgment of gap acceptance. This feature is beneficial when the green ball phase is active and/or when the signal changes from green to yellow, but not when the green arrow is active. This feature is supposed to benefit older drivers who may have compromised gap acceptance abilities (Staplin et al., 1997). Increased sight distance may increase driver's confidence resulting in smoother and faster turn. Consequently, we expect lateral acceleration and yaw to be lower and speed to be greater for the improved intersection. No difference in forward acceleration is expected because drivers may accelerate equally in order to drive through the gap in traffic, depending on their gap acceptance judgment (FARS, 1998; IIHS, 2000; Staplin & Lyles, 1991).

Maneuver 4: Separate Lane Signals with Protected Left Turn (PLT) Phase—The function of separate lanes is to increase safety and traffic flow (the number of vehicles that can pass through an intersection). The protected left turn (PLT) signal phase serves to eliminate the driver's decision of when to turn. Thus, it should reduce the need to make gap acceptance judgments and in turn decrease the magnitude of acceleration required during the turn (Staplin et al., 1997). Thus, the turn phase of the improved intersection is expected to exhibit smaller yaw and lateral acceleration values and faster speed compared to the unimproved intersection. Lesser forward acceleration is expected because the protected left turn phase should prevent drivers from needing to accelerate in order to drive through a gap in traffic (FARS, 1998; IIHS, 2000; Staplin & Lyles, 1991).

Maneuver 5: Intersection with Roadways Intersecting at 90 Degrees—Most road intersections require drivers to make a 90 degree turn. For a variety of social and economic reasons a minority of intersections have been constructed with roadways intersecting angles that deviate from this standard type. In this study drivers were required to turn at an acute intersection of less than 75 degrees. Negotiating the acute angled intersection (unimproved) was expected to require the driver to reduce speed and/or increase the muscular effort of turning the wheel. Older drivers were expected to experience increased difficulty when making such tight turns, resulting in less rotation of the steering wheel (McKnight & Steward, 1990) and producing greater positional errors during the turn. Accordingly, we expected greater lateral stability (less lateral acceleration and yaw), stable longitudinal acceleration, and higher speeds for the 90-degree turn and fewer errors recorded by the evaluators. Furthermore, we expected superior performance by the younger drivers and fewer behavioral errors.

PURPOSE AND HYPOTHESES

For this study we used kinematics measures from an instrumented vehicle and behavioral data (driver error) during on-road evaluations. We investigated the effects of improved versus unimproved intersections (for the turn phase only) and determined whether negotiation of these intersections was safer (vehicular stability and driver confidence) for both older (65–85 years) and younger (25–45) drivers.

We hypothesized that at the improved intersections kinematics performance would in general exhibit:

1. less yaw and lateral acceleration, indicating fewer deviations from the idealized curved path during the turn and thus greater vehicle stability;
2. higher speed and lower longitudinal acceleration, indicating greater driver confidence;
3. compared to younger adult drivers older drivers will exhibit greater yaw and lateral acceleration as well as lower speeds; and
4. older drivers will exhibit higher numbers of behavioral errors, especially for the unimproved intersections.

Conversely, we expected turning at the unimproved intersections to be more erratic resulting in higher yaw, higher lateral, longitudinal and combined acceleration, and lower speeds.

METHODS

Sample

Participants who met our inclusion criteria were recruited from North Central Florida via paid advertisements in newspapers, flyers distributed to aging service centers (e.g., Area Agency on Aging [AAoA]), health clubs, apartment complexes, community centers, open houses held at the University of Florida's Gator-Tech Smart House, and by word-of-mouth referrals. Approval of the research plan was obtained from the University of Florida's Institutional Review Board. All participants who met the inclusion criteria completed a telephone and informed consent form before enrolling in the study.

The inclusion criteria were: having a valid U.S. driver's license, age (young = 25–45 years; older = 65–85 years), mental status (a score of at least 24 on the Mini Mental Status Exam [MMSE: Folstein & Folstein, 1975] and completing the Trails B [Reitan, 1958] 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 were: having seizures within the past year and having major psychiatric or physical disorders influencing functional status. A total of 71 subjects participated in the study, 39 young subjects (mean = 33.54, $SD \pm 5.77$ years of age), and 32 older subjects (mean = 74.19, $SD \pm 5.94$ years of age).

Design

We examined the driving performance of old and young subjects through five pairs of intersections (*improved* versus *unimproved*) using kinematics data as well as driving-evaluation (behavioral) data. The pairs of intersections, referred to as maneuvers in this study, included the presence and absence of the following conditions: Maneuver 1: extended receiving lane; Maneuver 2: higher speed roads with right turn channelization at an intersection; Maneuver 3: left turn offsets; Maneuver 4: signalized intersections with separate lane signals for each lane; Maneuver 5: skewed angle intersecting roadways.

Procedure

The vehicle used for on-road evaluations was a 2004 Buick Century, a typical American car of the type that many older drivers use. It was instrumented to provide kinematics data that reflected vehicle control behavior of the driver. The instrumented vehicle, the instruments employed, the data acquisition system, and the derived measures were developed by the researchers of the University of Florida's National Older Driver Research and Training Center (NODRTC) in collaboration with the Department of Engineering. Figure 1 presents the setup and recording devices of the instrumented vehicle.

The road course consisted of an urbanized and residential street network in Gainesville, Florida. Embedded in the road course were 10 test signalized intersections, five of which are referred to as *improved*, consistent with recommendations in the FHWA design guidelines for improving performance and safety of older drivers. On average, subjects required slightly more than an hour to complete the road course. Travel through the intersections of the road course was the same for all subjects. The course was designed to balance the order of exposure of the improved and unimproved intersections. For two of the intersection comparisons, the *improved* intersection preceded the unimproved ones. For the remaining three pairs, the unimproved intersection preceded the improved intersection. Between the intersection pairs were a total of 19 non-test intersections that

Figure 1 Setup and recording devices in the trunk of the instrumented vehicle.

subjects were required to negotiate in order to complete the road course. None of the comparison sites were adjacent to one another; the number of intervening test intersections ranged from 1 to 5. Although there is a possibility of order effects it is unlikely that the arrangement of the intersections influenced the performance of drivers in this study.

The driving evaluator, sitting in the passenger seat of the test vehicle, provided verbal instructions to the subjects, well in advance (about 500 feet) of the next intersection, to orient the driver to the next demand. Additional conversation in the test vehicle was limited to a minimum. The testing occurred during the summer months of 2005, under the most perfect conditions, which included optimal weather conditions, non-peak traffic hours, and daylight hours.

The road course and maneuver location protocol of these intersection were based on the FHWA guidelines for intersections developed in collaboration with the Gainesville Traffic Engineering Department, geometrically matched by the city engineer and a driving consult, and pilot-tested by our driving evaluators. The rationale for inclusion of the specific test intersections are displayed in Table I. Due to a defect in a traffic control device one month into testing, one improved intersection, Maneuver 4, was tested at a different location with apparent similar guideline features.

Measurement

Kinematics, or vehicle control responses, included yaw (radians/sec), lateral (g forces), longitudinal (g forces), combined overall lateral and longitudinal control accelerations (g forces), and speed (mph). We used the maximum of these measures as we believe those will be most specific to the anticipated changes. Stability measures were obtained from a lateral accelerometer and an angular rate sensor in the car during road tests, and were computed through algorithms using a Matlab (Version 7.0.4) software program. Additionally, four cameras recorded the drivers' head movements and the forward and rear roadway scenes.

Behavioral data consisted of the subject's performance recorded by the driving evaluator as error or error free at each of the 10 signalized intersections in the residential areas of Gainesville. The eight driving behaviors included vehicle position, lane maintenance, speed, yielding, signaling, visual scanning, adjustment to stimuli/traffic signs, and gap acceptance (left turn only). Participant errors were scored and indicated with discrete continuous responses. Higher numbers indicated that more errors were made. Additionally driving evaluators supplemented the error data with general comments on conditions at the intersection (e.g., stopping vs, no stopping), traffic conditions (e.g., traffic flow), weather conditions (e.g., cloudy or full sun), or other subject behaviors (e.g., emotional state).

Data collection

Participants engaged in a telephone interview, brief clinical assessment, and an on-the-road driving assessment. A trained evaluator using an instrumented vehicle conducted all assessments. The trained driving evaluator, sitting in the passenger seat of the car, used a standardized road assessment performance (Justiss et al. 2006) sheet to record driving errors (behavioral data) as the subjects drove the road course. Video footage, obtained from the four cameras, was used for training of the four driving evaluators. The interrater reliability among the evaluators was high (intraclass correlation coefficient = 0.80–1.00). Kinematics data were entered and managed using Matlab (Version 7.0.4) software, while behavioral data were entered and managed in a MS Access database. All data were then imported to MS Excel, SPSS Version 13.0 (2005), and SAS Version 9.0 (1999) for analyses.

Analyses

A power analysis with *alpha* = 0.05 and *beta* = 0.80 with a moderate effect size and attrition rate of 20% yielded a requirement of 109 participants. Ninety-eight subjects performed all aspects of the evaluation. Of these, 21 had missing or incomplete data, resulting in analysis of data from 71 (39 young and 32 old) subjects. The kinematics data included maximum of combined, longitudinal, and lateral acceleration, yaw, and maximum speed during the turn phase of maneuvering at the intersection. To test for the effect of age and road condition we analyzed the normally distributed kinematics data using a 2×2 repeated measures ANOVA; the within-subject variable was intersection condition (improved vs. unimproved) and the between-subject variable was age (young vs. older). Behavioral data were expressed as the total number of errors for each of the five maneuvers. Differences between errors made for the improved versus unimproved conditions were computed for each subject. The paired data, not normally distributed, for each maneuver were analyzed separately using non-parametric 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

Of the 71 subjects, the 39 older subjects had 13 (40.6%) females and 19 (59.4%) males; the younger subjects had 24 (61.5%) females and 15 (38.5%) males.

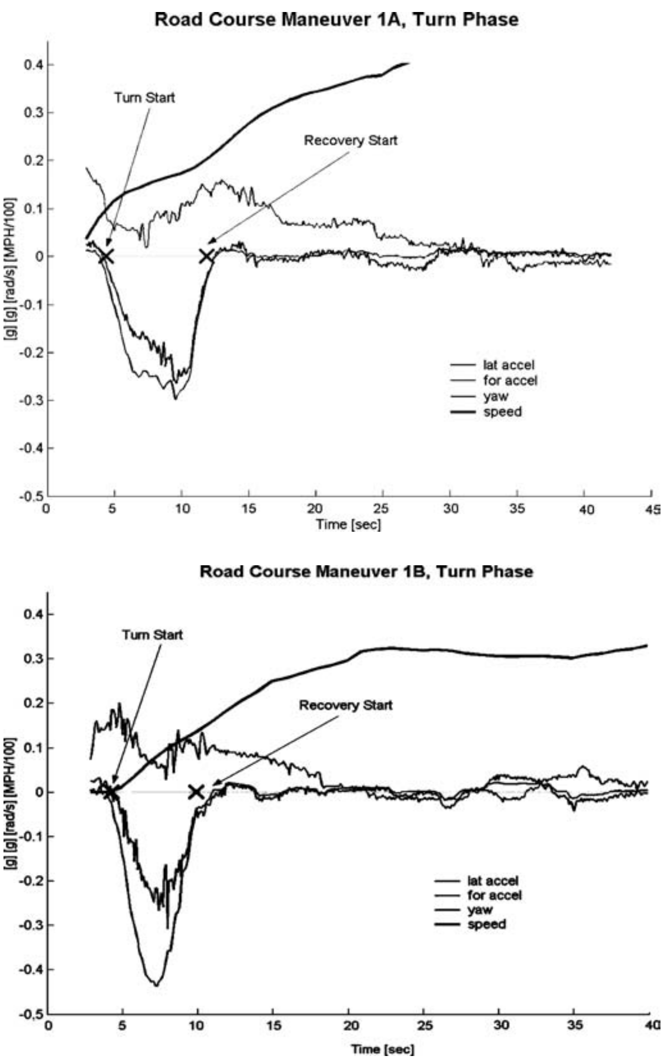

Figure 2a and b Graphs plotting the kinematics data for maneuver 1A (improved intersection) and maneuver 1B (unimproved intersection), indicating smaller yaw and lateral acceleration, but greater speed, as expected, for maneuver 1A (improved intersection).

Results indicated statistically significant findings between the improved and unimproved road conditions. Kinematics data for maneuver 1 showed a statistically significant decrease in maximum combined acceleration ($F = 9.07$; $p \leq 0.01$), maximum lateral acceleration ($F = 8.66$; $p \leq 0.01$), and maximum yaw ($F = 90.06$; $p \leq 0.01$) for the improved conditions, and statistically significantly greater speed ($F = 141.35$; $p \leq 0.01$) for the improved conditions. Decreased side forces indicated better lateral control or stability during the turn, whereas increased speed indicated greater control or confidence during turning. Figures 2a and 2b illustrates the smaller yaw and higher speed evident for the improved intersection of Maneuver 1a.

Kinematics data for Maneuver 2 showed a statistically significant decrease in maximum combined acceleration ($F = 19.50$; $p \leq 0.01$), maximum lateral acceleration ($F = 71.50$; $p \leq 0.01$), and maximum yaw ($F = 59.33$; $p \leq 0.01$) for the improved conditions, and statistically significantly greater speed ($F = 11.53$; $p \leq 0.01$) for the improved conditions. An interaction effect was indicated for maximum lateral acceleration: age $\times$ intersection ($F = 4.45$; $p = 0.04$). Compared to the younger drivers the older drivers had a lower mean on the improved intersection, but a higher mean on the unimproved intersection.

Maneuver 3 demonstrated statistically significant differences in the kinematics data, but in the opposite direction than expected. The data showed a statistically significant increase in maximum combined acceleration ($F = 4.87$; $p = 0.03$) and maximum yaw ($F = 50.11$; $p \leq 0.01$) for the improved conditions, meaning that increased longitudinal and side forces indicate poorer longitudinal and lateral control, or stability, during the turn phase of the improved intersection. A statistically significant age effect is observed ($F = 5.26; p = 0.02$), with the older drivers showing a higher mean for maximum yaw, meaning that they had more side forces during the turn phase of this intersection, as expected.

Kinematics data for Maneuver 4 showed a statistically significant increase in maximum combined ($F = 16.34$; $p \leq 0.01$), maximum longitudinal ($F = 11.21$; $p \leq 0.01$), and maximum lateral acceleration ($F = 14.79$; $p \leq 0.01$) for the improved conditions, indicating poorer longitudinal and lateral stability during the turn phase of the improved intersection. However, the data showed a statistically significantly lesser maximum yaw ($F = 47.89$; $p \leq 0.01$) and, consistent with that, greater maximum speed ($F = 14.91$; $p \leq 0.01$) for the improved conditions, indicating greater control during turning. A statistically significant age effect is observed for maximum yaw ($F = 4.60; p = 0.04$), with the older drivers showing a smaller mean, indicating that they had less side forces during the turn phase of this intersection.

Kinematics data for Maneuver 5 showed a statistically significant decrease in maximum combined acceleration ($F = 82.71$; $p \leq 0.01$), maximum lateral acceleration ($F = 93.84$; $p \leq 0.01$), and maximum yaw ($F = 300.85$; $p \leq 0.01$) for the improved conditions.

Behavioral data for the two improved left turn maneuvers, maneuver 1 (Wilcoxon 359.5; $p = 0.01$) and maneuver 5 (Wilcoxon 331.0; $p = 0.01$) showed that drivers had statistically significantly fewer errors. For Maneuvers 2 and 3 the behavioral data showed no statistical significance for intersection or age differences. The behavioral data for Maneuver 4 were consistent with the combined, longitudinal, and lateral acceleration kinematics data, showing drivers had statistically significantly more errors (Wilcoxon 359.0; $p = 0.01$) on the improved intersection. For total driving errors, for all maneuvers grouped together, a statistically significant difference was detected for age (Wilcoxon 1339.50; $p = 0.03$) in the favor of the older drivers.

DISCUSSION

Table II provides a summary of the kinematics and behavioral data by maneuver and age group for the improved and unimproved intersections. Generally, we discerned that yaw was the most sensitive measure for left turns and forward and lateral

Table II Summary table for kinematics and behavioral data for 5 maneuvers n =71 ($n_{young} = 39$, $n_{old} = 32$)

	Maximum combined acceleration (g)	Maximum longitudinal acceleration (g)	Maximum lateral acceleration (g)	Maximum yaw (radians/sec)	Maximum speed (mph)	Behavioral data (number of errors)
Maneuver 1	I < U Y = O	I = U Y = O	I < U Y = O	I < U Y = O	I > U Y = O	I < U Y = O
Maneuver 2	I < U Y = O	I = U Y = O	I < U Y = O	I < U Y = O	I > U Y = O	I = U Y = O
Maneuver 3	I > U Y = O	I = U Y = O	I = U Y = O	I > U Y < O	I = U Y = O	I = U Y = O
Maneuver 4	I > U Y = O	I > U Y = O	I > U Y = O	I < U Y > O	I > U Y = O	I > U Y = O
Maneuver 5	I < U Y = O	I = U Y = O	I < U Y = O	I < U Y = O	I = U Y = O	I < U Y = O
All maneuvers						Y > O
% Of measures showing superior performance for improved intersection (no difference in parentheses)	60 (0)	80 (20)	60 (20)	80 (0)	60 (40)	40 (40)
% Of measures showing superior performance for older group (no difference shown in parentheses)	0 (100)	0 (100)	0 (100)	20 (60)	0 (100)	0 (100)

I = improved; U = unimproved; Y = young; O = older; = Is equal; > Is statistically significantly greater; and < Is statistically significantly smaller.

acceleration the most sensitive for the right turn. The content and interpretation of this table are discussed below.

Maneuver 1: All kinematics measures of intersection performance met our expectations and we can conclude that the improved intersection design (extended receiving lane) resulted in better performance than the unimproved intersection. There were no differences between young and old drivers for intersection type. The behavioral data show fewer errors on the improved intersection, but no differences between age groups.

Maneuver 2: All kinematics measures of intersection performance met our expectations and we conclude that the improved intersection (acceleration lane with enhancements) resulted in better performance. The interaction effect suggests that, compared to the younger drivers, the older drivers had improved stability as they negotiated the turn of the improved intersection, benefiting more from the channelization and acceleration lane, but this needs to be interpreted with caution due to effect of chance. The behavioral measures showed no difference between the two intersections or between age groups.

Maneuver 3: With the exception of maximum longitudinal acceleration, no other kinematics measures of intersection performance met our expectations, suggesting that driver control during the turn phase intersection without the left turn offsets is less than when drivers negotiated the comparison intersection. Upon further examination of the unimproved intersection, we discovered that the single lane before the turn developed into three lanes after the turn, meaning that the drivers could make the turn in a more forgiving fashion. The improved intersection had only one lane before and after the turn, requiring the drivers to stay within the narrow boundaries of one lane. This difference in road geometry may have produced a confounding effect on the improved intersection. The evaluator's data also showed that for both the improved and unimproved intersection, a red arrow was present in the majority of the cases, meaning that the drivers had to proceed from a complete stop to make the turn, thereby eliminating the potential benefit of the left turn offset (improved feature for Maneuver 3).

Older drivers exhibited greater yaw during the turn, suggesting a less controlled maneuver by that group. The behavioral measures show no difference between the two intersections or between age groups.

Maneuver 4: Lesser yaw and higher speed during the turn favored the improved intersection (enhanced lane markings and signing) but these measures are offset by greater acceleration and a greater number of behavioral errors. Younger drivers exhibited a greater yaw during the turn. The improved intersection was proven to be confounded due to substituting this intersection with an additional one as a result of traffic control device failure. Thus, although some data show a guideline benefit to the drivers we remain inconclusive on the overall benefit of the FHWA guidelines on this intersection.

To understand why the acceleration and behavioral results differed from what we expected, we performed post hoc analyses. Recall that, due to traffic control device failure, the improved condition of this intersection had to be re-assigned to a different location. We examined the effect of changing the geographic location of this improved maneuver (*old* 4 and *new* 4), on the kinematics measures. The kinematics data for old improved Maneuver 4 ($n = 19$, $n_{young} = 13$, $n_{old} = 6$), showed a statistically significant increase for maximum combined acceleration indicating greater longitudinal forces during the turn phase of this intersection. The new improved Maneuver 4 ($n = 52$, $n_{young} = 26$, $n_{old} = 26$) showed a statistically significant increase for maximum combined and lateral acceleration, yet a statistically significant decrease in maximum yaw and a significant increase in speed. Therefore, we also examined total stops versus no stops, per age group, for improved versus unimproved (within-subject variable) intersections. For stopping at the improved intersection, maximum combined acceleration was statistically significant ($F = 4.79$; $p = 0.04$). For not stopping, all the measures for intersection type were statistically significant. For the improved intersection, all the acceleration measures and maximum speed had higher average mean scores, while maximum yaw had a lower mean score. An age effect existed ($F = 21.72$; $p = 0.01$) for maximum longitudinal acceleration in the favor of the older drivers, who had lower mean scores than the younger drivers. So, all drivers showed higher values of maximum lateral acceleration for the old and new improved intersection.

However, compared to the unimproved intersection the improved intersection had a lower value of maximum yaw. Normally these two measures are correlated (i.e., if yaw is greater then so is lateral acceleration). The reason for the disagreement can be explained by examining the governing equations and noticing that the maximum speeds differ significantly. The equations for lateral acceleration and yaw are defined in Eqs. (1) and (2), respectively.

$$a_l = \frac{v^2}{r}; \tag{1}$$

$$\omega = \frac{v}{r}, \tag{2}$$

where v is velocity and r is radius of curvature.

Yaw is proportional to velocity and lateral acceleration is proportional to the square of the velocity. Therefore, velocity has a greater affect on lateral acceleration than it does on yaw. The statistics showed that drivers had a lower speed for the unimproved intersection, but a higher rate of rotation (yaw). The opposite is true for the improved intersection. Since the values for maximum lateral acceleration are almost the same for the improved and unimproved intersections, we surmised that the unimproved intersection had a smaller radius of curvature. Accordingly we concluded that differences in the road geometrics confounded the findings of this maneuver.

Maneuver 5: All kinematics measures of intersection performance, with the exception of speed during the turn, favored the improved intersection over the unimproved one (acute angle). The behavioral data show fewer errors on the improved intersection but no differences between age groups.

Errors across all Maneuvers 1–5: The behavioral data for total driving errors, for all maneuvers, indicated an age effect in the favor of the older drivers, providing early empirical support to error reduction following implementation of the FHWA intersection guidelines (Staplin et al., 2001) for the turn phase.

Certain limitations must be considered, first for the kinematics measures: Compared to Maneuvers 1, 2, and 5, Maneuver 3 demonstrated less effectiveness for the FHWA intersection guideline application. But it is premature to conclude that the guideline features in Maneuver 3 did not enhance safety, as this interpretation can only be made once analysis of all three phases (approach, turn, and recovery phases) of the intersection is completed. Also, although all of these kinematics measures are considered indicators for safety, we do not know what the relationships are between these indicators and real-life crash situations. For the behavioral measures data indicated that older drivers committed more errors than younger drivers on the unimproved intersections but fewer errors than the younger drivers on the improved intersections. Yet, we are limited by the Wilcoxon method to infer interaction effects. Using parametric statistics, follow-up analyses may clarify interaction effects as well as type of error per type of maneuver by age group. Older driver safety is a developing science and as psychometrically sound behavioral measures are developed, researchers may wish to validate our findings.

This study examined the effectiveness of the FHWA intersection guidelines to implementing safe road conditions for five improved, matched with five unimproved, intersections (Staplin et al., 2001), and quantified kinematics and behavioral data for the turn phase of these intersections showing effects on the safe driving performances of younger and older adults. We conclude that Maneuver 1, the extended receiving lane; Maneuver 2, the right turn with channelization and acceleration lanes; and Maneuver 5, the intersection with roadways intersecting at 90 degrees, provide evidence that the FHWA intersection guidelines are effective for driver safety, benefiting older and younger drivers alike. Maneuver 3 was confounded by existing roadway geometrics (e.g., three lanes to turn into for the unimproved intersection, versus one lane to turn into for the improved intersection). Maneuver 4 was confounded by changing the improved intersection to a different geographic location. From the behavioral measures (error data), fewer errors were made on maneuver 1 and 5 by all drivers. Although an age effect was observed for older drivers (making fewer errors) across all improved maneuvers, this needs to be interpreted with caution until validated with parametric statistics.

This study brings empirical intersection design and safety information for engineers and city planners to consider as they plan and develop intersections. Future researchers may want to use the conceptual and analytical framework of this study to determine the effectiveness of other FHWA guidelines. Accepting that these intersection design guidelines benefit younger and older drivers alike, opens plausible policy-making opportunities in the design of safe roadway systems to benefit the broad spectrum of adult drivers.

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REFERENCES

Campbell KL. (1993) Recent Research in Developing Accident Typologies. Human Factors Research in Highway Safety. Transportation

Research Circular 414, 34-38. Transportation Research Board, Washington, DC.

Centers for Disease Control and Prevention. Injury Fact Book. Older Adult Drivers 2004. Available at: http://www.cdc.gov/ncipc/fact_book/18_Older_Adult_Drivers.htm. Accessed May 14, 2004.

Council FM, Zeeger CV. (1992) Accident Analysis or Older Drivers and Pedestrians at Intersection Task B Working Paper, Publication No. DTFH61-91-C-00033, Federal Highway Administration, Washington, DC.

Dellinger aM., Langlois Ja, Li G. (2002) Fatal Crashes Among Older Drivers: Decomposition or Rates into Contributing Factors. *Am. J. Epidemiol*., Vol. 155, pp. 234–241.

Eberhard J. (1996) Safe Mobility for Senior Citizens. International Association of Traffic Safety Services Research, Vol. 20, 29–37.

Fatal Accident Database (1998) U.S. Department of Transportation, National Highway Traffic Safety Administration, Washington, DC.

Federal Highway Administration (2004) Intersection Safety, Facts and Statistics. Washington, DC. Available at: http://safety.fhwa.dot.gov/intersections/inter_facts.htm. Accessed June 9, 2006.

Folstein,M, Folstein S. (1975) "Mini-Mental State": A Practical Method for Grading the Cognitive State or Patients for the Clinician. *J. Psych. Res*., Vol. 12, pp. 189–198.

Insurance Institute for Highway Safety (IIHS). (2000) Elderly, in *IIHS Fatality Facts*. IIHS, Washington, DC.

Insurance Institute for Highway Safety (IIHS) (2003) *Fatality Facts, Older People*. Arlington (VA): IIHS. Available at: http://www.highwaysafety.org/safety_facts/ fatality_facts/older_people.htm. Accessed January 28, 2004.

Justiss M.D, Mann WC, Stav,W, Velozo C. (2006) Development of a Behind-the-Wheel Driving Performance Assessment for Older Adults. *Topics Geriatric Rehab*., Vol. 22, pp. 121–128.

Matlab (Version 7.0.4) (2005). R14). Copyright 1984-2005 by MathWorks, Inc. USA: MathWorks, Inc.

McGwin G., Sims R, Pulley L., Roseman, JM. (2000) Relations among Chronic Medical Conditions, Medications, and Automobile Crashes in the Elderly: A Population-Based Case-Control Study. *Am. J. Epidemiol*., Vol. 152, pp. 424–431.

McKnight aJ, McKnight AS. (1999) Multivariate Analysis or Age-Related Driver Ability and Performance Deficits. *Acc. Anal. Prev.*, Vol. 31, No. 5, pp. 445–454.

National Highway Traffic Safety Administration. (2003)Traffic Safety Facts 2003. Older Population. Retrieved August 28, 2004, from http://www-nrd.nhtsa.dot.gov/pdf/nrd-30/NCSA/TSF2003/809766.pdf

Reitan RM. (1958) Validity of the Trail Making Test as an Indicator of Organic Brain Damage. *Percept and Motor Skills*, Vol. 8, pp. 271–276.

Staplin L, Harkey D, Lococo K, Tarawneh M. (1997) Intersection Geometric Design and Operational Guidelines for Older Drivers and Pedestrians. Volume I: Final Report. Publication No. FHWA-RD-96-132, Federal Highway Administration, Washington, DC.

Staplin L, Lococo K. Byington,S, Harkey, D. (2001) Guidelines and Recommendations to Accommodate Older Drivers and Pedestrians. Publication No. FHWA-RD-01-051. US. Department of Transportation, Federal Highway Administration, Washington, DC.

Staplin L, Lyles RW. (1991) Age Differences in Motion Perception and Specific Traffic Maneuver Problems. Transportation Research Record 1325. Transportation Research Board, Washington, DC.

SAS (r) Software Version 9. SAS Institute Inc., Cary, NC.

SPSS for Windows, Release Version 13.0.1. 2005 Chicago: SPSS Inc.