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Validating a driving simulator using surrogate safety measures

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Abstract

Traffic crash statistics and previous research have shown an increased risk of traffic crashes at signalized intersections. How to diagnose safety problems and develop effective countermeasures to reduce crash rate at intersections is a key task for traffic engineers and researchers. This study aims at investigating whether the driving simulator can be used as a valid tool to assess traffic safety at signalized intersections. In support of the research objective, this simulator validity study was conducted from two perspectives, a traffic parameter (speed) and a safety parameter (crash history). A signalized intersection with as many important features (including roadway geometries, traffic control devices, intersection surroundings, and buildings) was replicated into a high-fidelity driving simulator. A driving simulator experiment with eight scenarios at the intersection were conducted to determine if the subjects' speed behavior and traffic risk patterns in the driving simulator were similar to what were found at the real intersection. The experiment results showed that speed data observed from the field and in the simulator experiment both follow normal distributions and have equal means for each intersection approach, which validated the driving simulator in absolute terms. Furthermore, this study used an innovative approach of using surrogate safety measures from the simulator to contrast with the crash analysis for the field data. The simulator experiment results indicated that compared to the right-turn lane with the low rear-end crash history record (2 crashes), subjects showed a series of more risky behaviors at the right-turn lane with the high rear-end crash history record (16 crashes), including higher deceleration rate ($1.80 \pm 1.20\,\mathrm{m/s^2}$ versus $0.80 \pm 0.65\,\mathrm{m/s^2}$), higher non-stop right-turn rate on red (81.67% versus 57.63%), higher right-turn speed as stop line (18.38 ± 8.90 km/h versus 14.68 ± 6.04 km/h), shorter following distance (30.19 ± 13.43 m versus 35.58 ± 13.41 m), and higher rear-end probability (9/59 = 0.153 versus 2/60 = 0.033). Therefore, the relative validity of driving simulator was well established for the traffic safety studies at signalized intersections.

Keywords: Driving simulator; Signalized intersections; Geo-specific database modeling; Speed validation; Safety validation; Rear-end crashes

1. Introduction

With the progress of computer science and electronic engineering in recent years, simulation technologies are being rapidly developed and enhanced. Both flight and driving simulators have been broadly used for training, vehicle design, or safety research. The overall value of using flight simulators for training has been well established (Orlansky and String, 1977). Because simulators are cheaper to use than operational aircraft, they have often been considered substitute aircraft rather than training devices (Eddowes and Waag, 1980). Military simulation also offers a potential training media for learning and practicing combat skills (Alluisi, 1991). Coinciding with this technological improvement, multi-disciplinary investigations and analyses using driving simulators have been conducted in the traffic engineering area, such as pavement marking effect (Horberry et al., 2006), traffic signs (Dutta et al., 2004), gap acceptance behavior (Alexander et al., 2002), passing maneuver (Jenkins and Rilett, 2005), crash avoidance study (Smith et al., 2002), driving distraction due to mobile phones (Rakauskas et al., 2004), and so on.

The use of an advanced driving simulator has many advantages over similar real-world or on-road driving research, including experimental control, efficiency, expense, safety, and ease of data collection (Nilsson, 1993). However, very few studies focused on exploring driving simulators as a test tool to evaluate traffic safety quality of highways. Through constructing highway geometries and environments in the high-fidelity simulator system, the simulator experiments under the three-dimension virtual reality are possible to reproduce dangerous

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driving conditions and situations. Thereby, driving simulators have a potential to identify highway design problems, explain interaction between drivers and roadway surroundings, and most importantly, explore effective countermeasures to enhance the quality of traffic safety and operation. In support of this concept, appropriate simulator validity research is needed and should not only focus on comparing drivers' behaviors between simulator and field but also evaluating if the driving risk in simulator can reflect crash propensity in the real-world.

Jamson (1999) states that there exist two primary areas of simulator validation, physical and behavioral validation. Physical validity measures the degree to which the simulator dynamics and visual system reproduce the vehicle being simulated. As the world's most sophisticated driving simulator, the U.S. National Advanced Driving Simulator (NADS) needs a detailed, highly accurate vehicle dynamics simulation to predict the movements of the simulated vehicle in response to both control and disturbance inputs. Several types of vehicle dynamics models in NADS has been validated at the absolute validity level, including Ford Taurus, Jeep Cherokee, Chevrolet Malibu, and a tractor–semitrailer (Salaani and Heydinger, 2000). Behavioral validation refers to a simulator's ability to induce the same response from a driver as would be performed in the same situation in real life (Jamson, 1999). Blaauw (1982) proposed two types of driving behavioral validity: absolute validity (when the numerical values between the two systems are the same) and relative validity (when differences found between experimental conditions are in the same direction, and have a similar or identical magnitude on both systems).

Many previous validation studies related to driving speed behaviors have been conducted to evaluate if drivers have similar speed performances in driving simulators as those measured in the real-world or a real instrumented car. At the University of Central Florida, a study was conducted to evaluate if the fix-base driving simulator could provide a realistic driving experience (Klee et al., 1999). The results indicated that the drivers behaved similarly at 10 of 16 designated locations along the road, but the difference in mean speeds between the simulator and the field indicated a tendency of drivers to travel at slower speeds in the simulator. Godley et al. (2002) conducted a speed validation study that compared speed measurements of an instrumented car and the driving simulator in two separate experiments where the tested roadways contained transverse rumble strips at three sites, as well as three equivalent control sites without rumble strips. It was found that participants reacted to the rumble strips, in relation to their deceleration pattern on the control road, in very similar ways in both the instrumented car and simulator experiments, establishing the relative validities. However, the results failed in absolute validity because participants generally drove faster in the instrumented car than the simulator. Törnros's (1998) validation study for speed and lateral position evaluated driving behavior in a simulated road tunnel. He drew a similar conclusion that behavioral validity in absolute terms was not quite satisfactory, especially regarding the choice of speed, whereas relative validity was achieved for both speed and lateral position. Comparing field and simulator study results, Kaptein et al. (1996) found that generally absolute validity of route choice behavior is obtained; relative validity of speed and lateral control behavior is obtained; and the presence of a moving base and possibly a higher image resolution might increase the validity of a driving simulator.

In the Interuniversity Research Center for Road Safety (CRISS), a simulator speed validation study focused on the effectiveness of temporary traffic signs on highways (Bella, 2005). Speed measurements were conducted for both field observations and driving simulator experiments in the transition area, the activity area, the termination area, and the advance warning area. The results showed that differences between the speeds observed in the real situation and those measured with the simulator were not statistically significant and therefore validated the driving simulator in absolute terms. A further simulator validation study for highway deceleration lane design conducted by Bella et al. (2007) indicated that into the deceleration lane, the speeds in driving simulator were also similar to the field data, but in simulation, standard deviation is higher than in reality.

Another recent research was conducted to ascertain the validity of a driving simulator in determining the effectiveness of temporary traffic control devices in a work zone during nighttime hours. Spot speeds were observed in both field and driving simulator at three locations in a freeway work zone (McAvoy et al., 2007). However, it was found that the statistical tests indicated that a simulator study may not reproduce the mean travel speed of a field study for nighttime driving conditions through a work zone in either absolute or relative validity terms.

In addition, to validate the driving behavior of older adult drivers (60–90 years) in a PC-based simulator, Lee (2002) established an overall measure index to evaluated drivers' performances, such as driving speed, confidence on high speed, traffic rule compliance, decision and judgment, road use obligation, working memory, and so on. He found a covariance ($r^2 = 0.66$) between the two measures of the simulator and the actual vehicles and concluded that simulator usage was a safer and more economical method than the on-road testing to assess the driving performance of older adult drivers.

However, according to the literature review, there is no validation study that directly focused on a traffic safety measure. This study aims at investigating whether a driving simulator can be used as a valid tool to assess traffic safety at signalized intersections. Traffic crash statistics and previous research have shown an increased risk of traffic crashes at signalized intersections (FHWA, 2004; Abdel-Aty et al., 2005). In the United States, intersection/intersection-related crashes account for more than 45% of all reported crashes, and 21% of fatalities. How to diagnose safety problems and develop effective countermeasures to reduce crash rates at intersections is a key task for traffic engineers and researchers. In this study, a signalized intersection with as many important features (including roadway geometries, traffic control devices, intersection surroundings, and buildings) was replicated into a high-fidelity driving simulator. Through merging roadway blueprints, autoCAD files, and hand measurements into the visual database, the main geometry features of the intersection that matched the field location include curve radius, cross-section, marking design, median shape and location, traffic sign position, and driveway access location.

The specific intersection was selected because it was one of intersections with the highest crash frequencies in the Central Florida area. This simulator validity study was conducted from two perspectives, a traffic parameter (speed) and a safety parameter (crash history). For the speed validation, the four-approach operating speeds were, respectively, measured in both simulator and field, with a hypothesis that the speed measures in the driving simulator environment would be statistically similar to those at the real intersection. For the safety validation, two locations (higher rear-end risk versus lower rear-end risk) were identified at the intersection based on the intersection crash history analysis, with a hypothesis that the risk propensities for the two locations observed in the further simulator experiment would be analogous to the traffic crash propensities found in crash history analysis. The validation method and results in this study would be applicable to other studies using similar driving simulator equipment.

2. Methodology

2.1. Apparatus/equipment

The University of Central Florida (UCF) driving simulator was used in this research. The driving simulator has a motion base capable of operation with 6 degrees of freedom. It includes 5 channels (1 forward, 2 side views and 2 rear view mirrors) of image generation, an audio and vibration system, and steering wheel feedback. The simulated environment is projected at 180 degrees of field view and at a resolution of 1280 pixels × 1024 pixels. The driving simulation system is composed of the following components:

- Simulator Cab: Saturn Sedan, automatic transmission, air conditioning, the left back mirror, and the back mirror inside the cab.
- Simview: The software provides the graphical display based on the computation.
- Scenario Editor: The software helps researchers to edit traffic scenarios.
- APIs for reading real-time data: Application Programmer Interface (APIs) can read the real-time data from Simview. The sampling frequency is 60 Hz.

2.2. Simulator validation study process

This study started from identifying a signalized intersection as a research platform to conduct the simulator validity research. The study process (see Fig. 1) involved several research efforts:

- Geo-specific Modeling—Replicating the test signalized intersection in the UCF driving simulator system to create a visual database.
- Crash report analysis—Analyzing 4 years of crash reports for the intersection to identify significant crash patterns and risk propensities at different approaches.
- Speed measurements in field—Measuring vehicle's operating speeds at four approaches of the intersection in the field.
- Driving simulator experiment—Designing and running a driving simulator experiment to measure the subjects' driving performances in the simulator.
- Speed validation—Comparing speed measures in the simulator experiment to those observed in the field to conclude if drivers have similar driving behaviors.
- Safety validation—Comparing the surrogate safety measures using the risk propensities of driving behaviors at different intersection locations in the simulated experiment to those from crash history analysis to conclude if the risk propensities reflected in the driving simulator are corresponding to the findings from crash history analysis.

2.3. Intersection identification and crash report analysis

The Alafaya Trail (SR434) and E. Colonial Drive (SR50) signalized intersection was selected for this study (see Fig. 2). It is a major intersection (4 × 6) of state roads in Orange County and has one of the highest crash frequencies in Central Florida. Each approach at the intersection has two left-turn lanes and one right-turn lane. The intersection is skewed (81°) and the speed limits are 72.4 km/h (45 mph) for south-

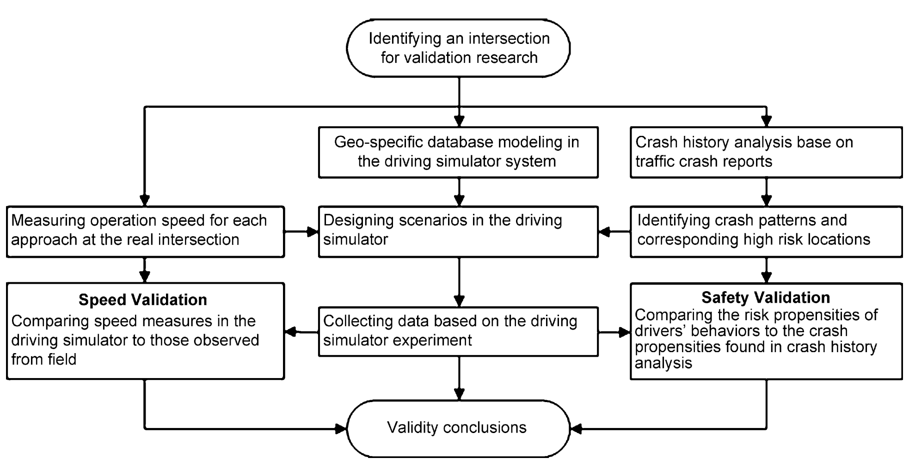

Fig. 1. Flowchart of the speed and safety validation study.

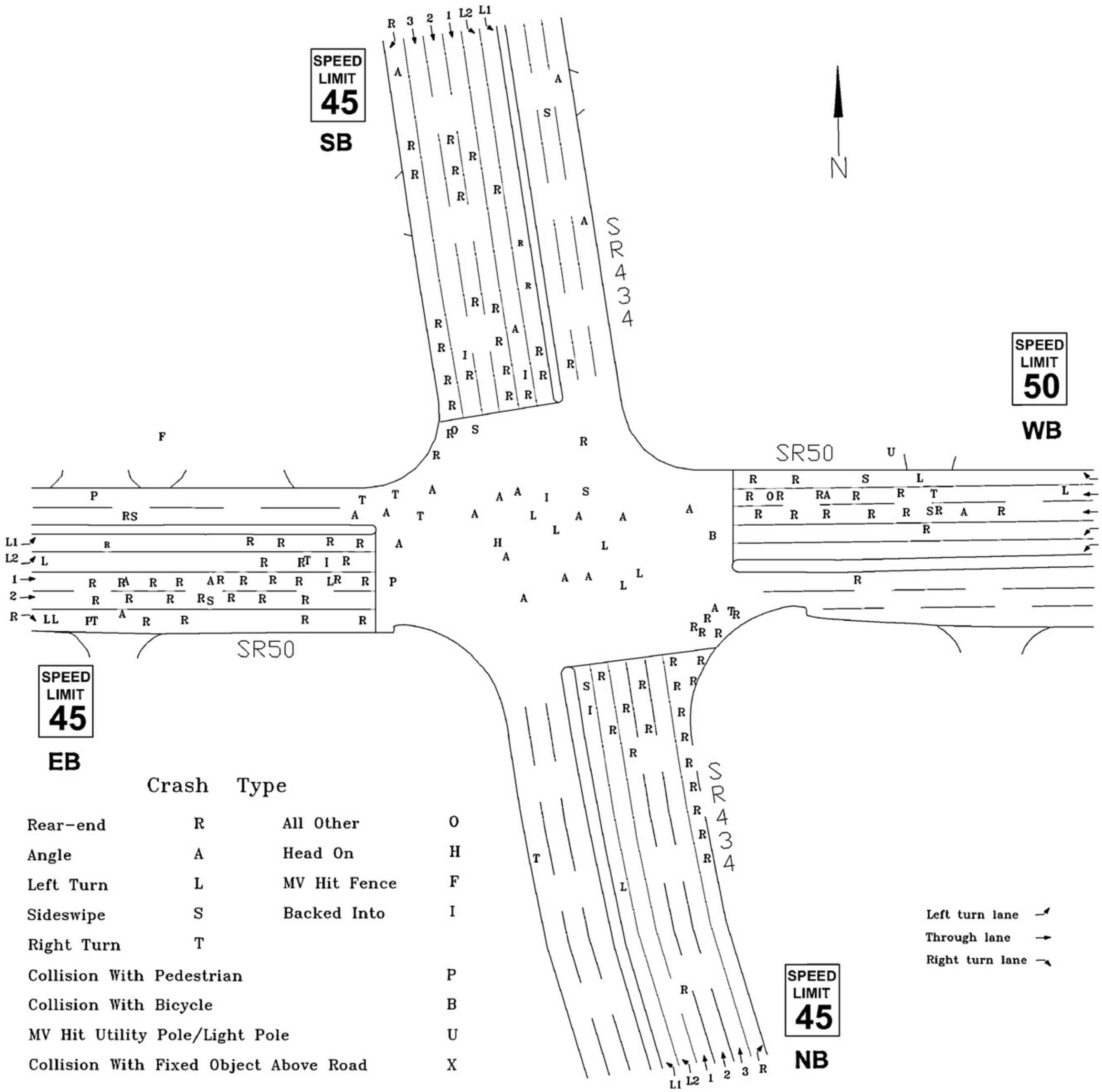

Fig. 2. Crash spot diagram for years 1999–2002.

bound (434SB), eastbound (50EB), and northbound approaches (434NB), and 80.5 km/h (50 mph) for the westbound approach (50WB).

Four years (1999–2002) of crashes at this intersection (SR434 and SR50) have been analyzed for the driving simulator validation study. The crash information was obtained from the Florida Department of Transportation Crash Analysis Reporting System. Table 1 shows crash type and frequency at the intersection within a 91.4-m (300-ft) radius from the center of the intersection. This intersection has experienced primarily rear-end crashes with a frequency of 95 and a relative frequency of 57.9%. The second most frequent type was angle (24% or 14.6%), followed by left-turn (12% or 7.3%), sideswipe (10% or 6.1%), and right-turn (8% or 4.9%). From the severity point of view there were 73 property-damage-only crashes, 90 injury crashes, and 1 fatal crash.

Furthermore, the crash spot diagram can be used to compare crash propensities of the intersection locations. Fig. 2 shows all types of crashes that happened at this intersection for the 4 years. In comparing the four approaches, it was found that the rear-end risk at the SR434 right-turn lanes was higher than that at the SR50 right-turn lanes. There was a total of 24 rear-end crashes occurring at SR434 right-turn lanes, 8 for 434SB and 16 for 434NB. During the same period, SR50 right-turn lanes had only 6 rear-end crashes, 4 for 50EB and 2 for 50WB. Thus, the 434NB right-turn lane had the largest rear-end crash propensity while the 50WB right-turn lane had the lowest rear-end crash propensity. This strong crash risk comparison between the two locations

Table 1
Crash frequency for years 1999–2002

First harmful event	1999	2000	2001	2002	Type Frequency	
Rear-end	21	29	18	27	95	57.9%
Angle	4	11	7	2	24	14.6%
Left turn	6	2	3	1	12	7.3%
Sideswipe	4	1	3	2	10	6.1%
Right turn	3	1	3	1	8	4.9%
Backed Into	3	1	0	0	4	2.4%
Collision with pedestrian	0	1	1	1	3	1.8%
All other	0	0	1	2	3	1.8%
Head- on	0	1	0	0	1	0.6%
Collision with bicycle	0	0	0	1	1	0.6%
MV hit utility pole/ light pole	0	0	0	1	1	0.6%
MV hit fence	0	0	0	1	1	0.6%
Collision with object above road	0	0	0	1	1	0.6%
Total	41	47	36	40	164	100.0%

can be used to develop the simulator experiment scenarios for the safety validation purpose. The hypothesis to be tested in the simulator experiment is that the rear-end crash risk at the 434NB right-turn lane is higher than that at the 50WB right-turn lane.

Further crash report analysis for those rear-end crashes reveals that most vehicles involved in the crashes are automobiles; males and females have almost equal rear-end crash involvement risk; there is a high crash rate of middle age drivers (25–64 years) involved in rear-end crashes; and almost all crashes happened because the drivers of the striking vehicles drove carelessly. From the police crash report narrative, for most rear-end crashes, the struck vehicle stopped to yield to the opposing traffic or signal change while the striking vehicle failed to stop simultaneously and proceeded to hit the rear of the front vehicle. Right-turn-on-red is permitted at all approaches for this intersection. Since the signal change interval length for each approach is same (yellow phase is 4.3 s and all red phase is 1 s), the difference in the rear-end crash risk between the 434NB and 50WB right-turn lanes is not due to the design of signal change interval, but more likely attributed to the difference in highway design features of the two approaches. Moreover, for both approaches there is no sight distance problem due to fixed sight obstructions.

2.4. Speed measurement in field

For the speed validation, free flow speeds at the real intersection were recorded for vehicles entering the intersection through each approach during the green phase, using a radar gun. These recordings for all the approaches were taken on Tuesday (05/02/2006) from 9:30 am to 5:00 pm. Two observers were placed around 50 m (164 ft) downstream of the approach; the radar gun was pointed towards the opposing flow; speeds of the oncoming vehicles located upstream of the intersection were recorded. The vehicles were carefully selected such that they were under free flow conditions. Specifically, after the green phase started and vehicles in queue were cleared, only the operating speeds of those vehicles which were not in a platoon were selected for data collection. There are 134 observations for 50WB approach, 104 observations for 50EB approach, and 91 observations for 434SB and 434NB each.

2.5. Geo-specific database modeling in the simulator system

Replicating a real-world driving environment into a simulated 3D virtual world is referred to as geo-specific database modeling. To provide drivers with a realistic driving experience, as many important features of the real intersection as possible were replicated in the driving simulator visual database. It consists of three essential components: the two intersecting roads (including traffic signs), the traffic signals, and the buildings (including important objectives close to the intersections, such as trees, advertisement boards, electricity poles, and so on). The modeled road geometry is a near replica of the actual roadway network within 366 m (1200 ft) in each of the four approaches, achieved by merging roadway blueprints, autoCAD files, and hand measurements into the visual database. The traffic signs including speed limit signs were positioned in the visual database corresponding to the locations at the real intersection. The traffic signals were created for all signal cases which occurred at this particular intersection. Even the "walk/do not walk" flashing signs were built and integrated into the Traffic Control Device (TCD). The timing diagram and actuator sequencing from the actual intersection was used to build the TCD model. Since the study mainly paid attention to the isolated intersection safety problems but not road network issues, the signal coordination plan with other intersections was not considered in the simulation database. The further replication of the highway environment beyond the 366-m range of the intersection was extended to one to two miles for each approach, using a less precise, although more efficient method. Fig. 3 illustrates the visual effect comparisons between virtual reality and the real intersection and the modeling scope of the intersection in the simulator system.

2.6. Simulator experiment design

2.6.1. Traffic scenario design

To validate the driving simulator using speed and safety parameters, a total of eight scenarios were designed in the driving simulation experiment. There were four scenarios designed for the speed validation and the other scenarios designed for the

(a)

(b)

(c)

Fig. 3. Geo-specific database modeling of the intersection. (a) Snapshots for Chevron Gas Station and Shell Service Center. (b) Snapshots at the southwest corner of the intersection. (c) Main modeling scope of the geo-specific database in the simulator system.

safety validation. In each traffic scenario, subjects started driving the simulator at 800 m upstream of the intersection and then approached to the intersection to execute the required driving maneuver. For the speed validation (see Fig. 4), subjects drove the driving simulator to cross through the intersection from the four intersection approaches, respectively. For the safety validation of the rear-end crash, the right-turn movements at the 434NB approach were designed as test scenarios (the higher risk location) and those at the 50WB approach were designed as base scenarios (the lower risk location). Since the rear-end risk is related to both leading vehicles (e.g. sudden stopping) and following vehicles (e.g. following too closely), right-turn maneuvers as leading role and following role were both designed for the rear-end safety test. From the police crash report narrative, drivers' responses to signal change played a key role in most rear-end crashes. Therefore, the signal change was designed as a critical traffic event in the safety validation scenarios. As a leading role (see Fig. 5a), there was no other vehicle in front of the simulator; when subjects were entering the right-turn lane and located at 100 m (328 ft) upstream from the stop line, the signal light changed from green to yellow to red. As a following role (see Fig. 5b), subjects would follow a vehicle to enter the right-turn lanes; after the leading vehicle encroached into the right-turn lane, it gradually slowed down; when it was located 60 m (197 ft) upstream from the stop line, the traffic signal will change from green to yellow; and when the leading vehicle approaches the intersection at 50 m (164 ft) away from the stop line, it would make a sudden brake from 48.3 km/h (30 mph) to zero with a high deceleration rate 6.4 m/s^2 (21.06 ft/s^2 or 0.65 g); then, the subject driving the following simulator had to respond to the event quickly in order to avoid a rear-end crash happening.

2.6.2. Participants

Age and gender of the subjects are two independent variables (factors) considered for this experimental design. Since this study aimed at using the real traffic parameters and crash history at the intersection to validate the driving simulator experimental results, the age categorization followed the actual driver population using the quasi-induced exposure method (Abdel-Aty et al., 1998; Stamatiadis and Deacon, 1997). Because very few crashes involved the older age group at the intersection, five age groups of interest are classified as Very Young (15–19), Young (20–24), Younger Middle-Aged (25–34), Middle Middle-Aged (35–44) and Older Middle-Aged (>45). Therefore, the

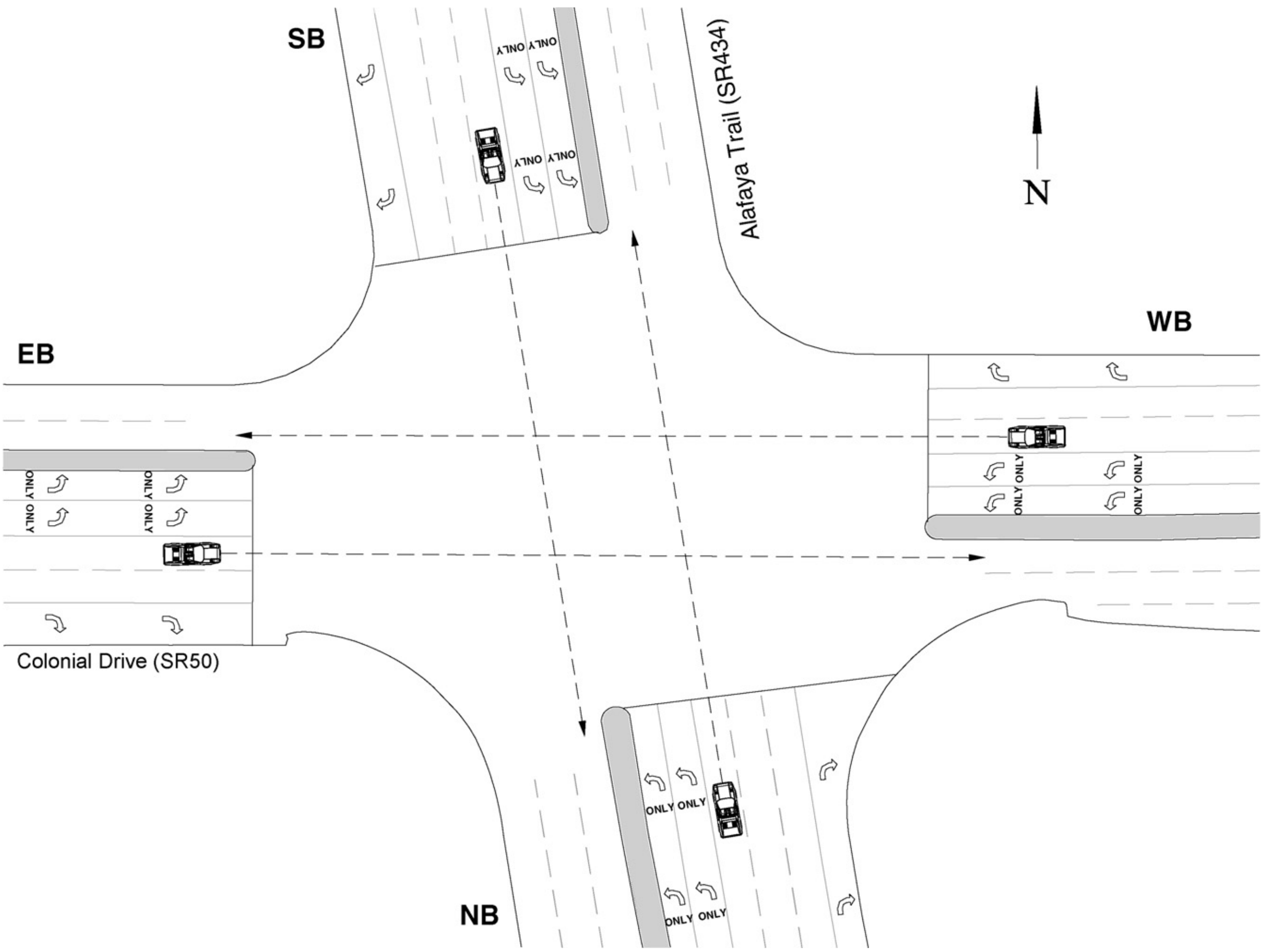

Fig. 4. Scenarios for speed validation.

experiment was a 5 (age) × 2 (gender) within-subject repeated measures design.

Table 2 shows the sample size by age and gender for each specific scenario. The subjects were carefully selected in such a way that they belonged to all age groups ranging from sixteen to greater than 45 and were evenly distributed among male and female groups. Due to the sickness effect, the eventual number of subjects ranged from 58 to 62 in the specific scenarios. Each subject was paid US$ 10 for running the experiment, in which the subject was asked to drive the eight scenarios. Every participant held a valid Florida's driver's license with at least 1 year of driving experience. Furthermore, based on a survey after the experiment, 47.7% of subjects traveled though this intersection daily, 34.1% traveled there once a week, 11.4% traveled there once a month, and 6.8% rarely traveled through the intersection.

Table 2
Subjects by age, gender, and scenario

Age group	Scenarios for speed validation								Scenarios for safety validation							
	50WB		434SB		50EB		434NB		434NB leading		50WB leading		434NB following		50WB following	
	Fe	Ma	Fe	Ma	Fe	Ma	Fe	Ma	Fe	Ma	Fe	Ma	Fe	Ma	Fe	Ma
16–19	5	8	6	7	5	6	4	6	5	8	5	8	5	6	4	6
20–24	6	8	6	8	8	8	7	8	7	8	6	8	6	8	7	8
25–34	5	9	5	8	5	9	5	9	5	8	5	8	5	9	5	9
35–44	5	8	5	7	4	7	4	7	5	7	5	6	4	6	4	7
>45	1	6	1	5	2	8	2	8	1	6	1	6	2	8	2	8
Subtotal	22	39	23	35	24	38	22	38	23	37	22	36	22	37	22	38
Total	61		58		62		60		60		58		59		60	

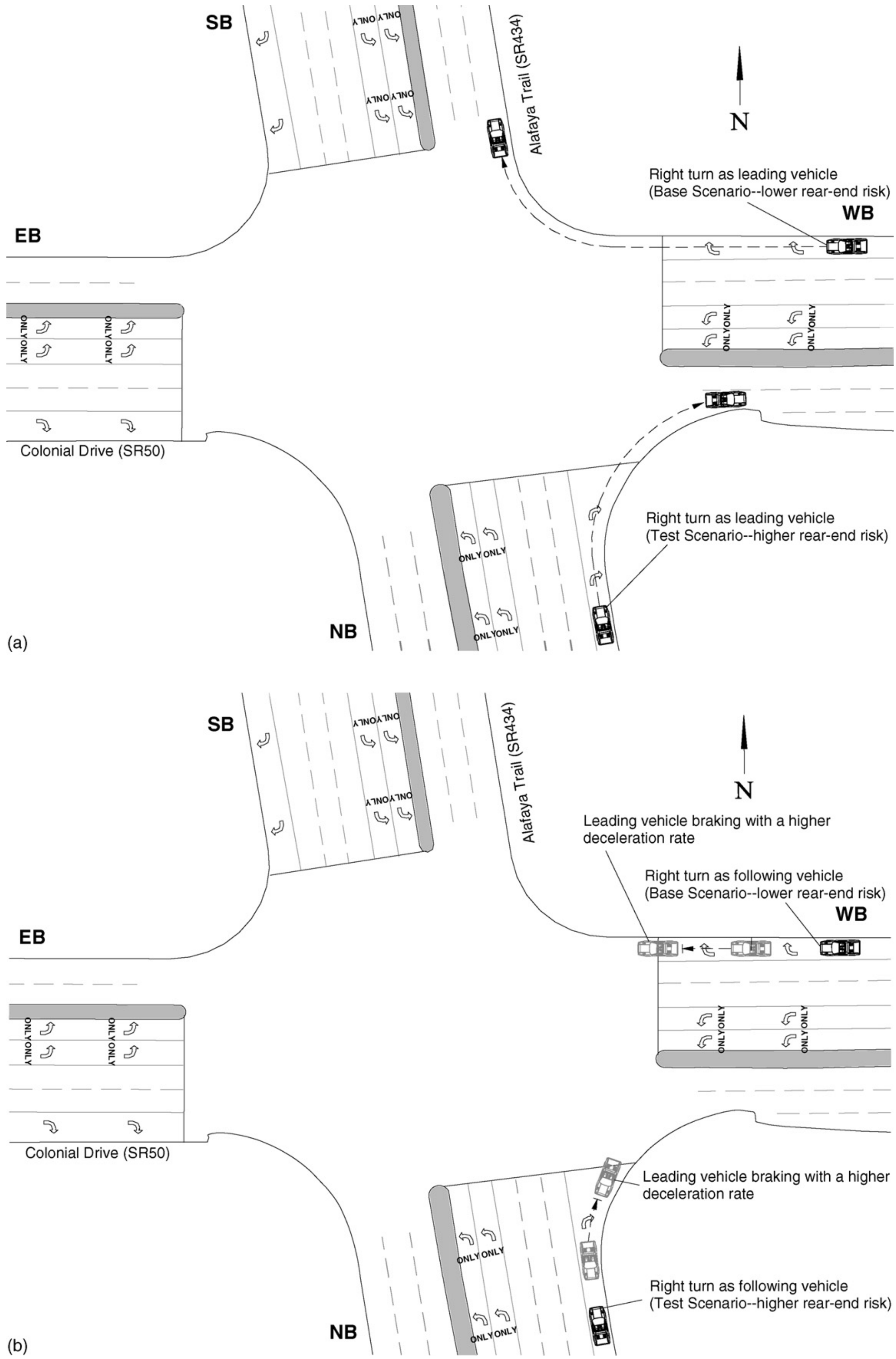

Fig. 5. Right-turn scenarios for safety validation. (a) Subjects driving the simulator as the leading vehicle. (b) Subjects driving the simulator as the following vehicle.

2.6.3. Experiment procedure

Upon arrival, the subjects were given an informational briefing about the driving simulator, and the subjects were asked to fill out and sign an informed consent form (per IRB). They were advised to adhere to traffic laws in the driving simulator and to drive as if they were in normal everyday traffic surroundings. The subjects were also notified that they could quit the experiment at any time in case of motion sickness or any kind of discomfort. Prior to the formal experiment, drivers were trained for at least 5 min to familiarize with the driving simulator operation. During the course of the practice, the subjects exercised selected maneuvers including straight driving, acceleration, deceleration, left/right-turn, and other basic driving behaviors.

After completing the familiarity course, the subjects performed the formal experiment with the 8 scenarios, which were randomly loaded for each driver so as to eliminate the time order effect and potential bias from subjects. Before running each scenario, experiment operators would instruct subjects what maneuver they should take. For the speed validation scenarios, subjects were instructed "keep going straight along the highway unless there is an indication to stop." For the safety validation scenarios, subjects were instructed "keep going straight along the highway, and when you see a signalized intersection, turn right at the intersection." For security and liability reasons, each subject was escorted to the simulator cabin to commence the experiment and he/she was allowed at least 2 min to rest before running the next scenario. Finally, when subjects completed the formal experiments, a survey was used to gather information about their evaluations on the fidelity of the driving simulator and the intersection.

2.6.4. Dependent measures

The operating speed is the only dependent measure in the speed validation scenarios. Corresponding to the speed measures in the field, the four-approach operating speeds under free flow conditions were, respectively, measured at 90 m upstream of the intersection when the traffic signal was green. In the safety validation scenarios, the dependent variables related to the right-turn driving behaviors were measured as safety surrogates to compare rear-end risk between the two selected locations. Table 3 lists the independent variables that were considered for safety validation in scenarios that subjects make right-turn maneuvers as either leading role or following role. If the driving simulator is a valid safety assessment tool, it is expected that corresponding to the crash history analysis, the more risky behaviors would be observed in the 434NB right-turn compared to the 50WB right-turn lane.

Table 4
Kolmogorov—Smirnov normality test for speed distributions (km/h)

Approach	Statistical parameters	Field study	Simulator study
434NB	N	91	60
	Mean	70.46	70.32
	S.D.	10.19	13.67
	Kolmogorov–Smirnov Z	0.808	0.810
	P-value	0.531	0.528
434SB	N	91	58
	Mean	68.07	70.79
	S.D.	11.15	12.83
	Kolmogorov–Smirnov Z	0.770	0.304
	P-value	0.594	1.000
50EB	N	104	62
	Mean	73.77	75.28
	S.D.	10.08	15.22
	Kolmogorov–Smirnov Z	0.829	0.633
	P-value	0.497	0.817
50WB	N	134	61
	Mean	72.57	76.59
	S.D.	10.13	14.31
	Kolmogorov–Smirnov Z	1.091	0.619
	P-value	0.185	0.838

3. Experiment results and simulator validity analysis

3.1. Speed validation

Three aspects of comparisons between field observations and simulator experiment results were considered in the study, including the Kolmogorov–Smirnov normality test for speed dis-

Table 3
Independent measures collected for safety validation

Independent variable	Variable description	
In scenarios that subjects make right-turn maneuvers as the leading role		
Spd100_L	Simulator speed measured at 100 m away from stop line in the right-turn lane	Continuous (km/h)
Spd80_L	Simulator speed measured at 80 m away from stop line in the right-turn lane	Continuous (km/h)
Spd60_L	Simulator speed measured at 60 m away from stop line in the right-turn lane	Continuous (km/h)
Spd40_L	Simulator speed measured at 40 m away from stop line in the right-turn lane	Continuous (km/h)
Spd20_L	Simulator speed measured at 20 m away from stop line in the right-turn lane	Continuous (km/h)
Spd0_L	Simulator speed measured at stop line in the right-turn lane	Continuous (km/h)
Full_STOP_L	Did driver fully stop at the right-turn lane?	Categorical (yes = 1; no = 0)
Ave_Del_L	The average deceleration rate in the right-turn lane	Continuous (m/s^2)
In scenarios that subjects make right-turn maneuvers as the following role		
Speed_F	Simulator speed measured when the leading vehicle started a sudden brake	Continuous (km/h)
Distance_F	Following distance to the leading vehicle measured when the leading vehicle started a sudden brake	Continuous (m)
Ave_DEL_F	The average deceleration rate in the right-turn lane	Continuous (m/s^2)
Crash_F	Is there a rear-end crash happening in the right-turn lane?	Categorical (yes = 1; no = 0)

Table 5
F-test for variance of speed and t-test for mean comparison of speed (km/h)

Approach	Statistical parameters	Field Study	Simulator Study
434NB	N	91	60
	Mean	70.46	70.32
	S.D.	10.19	13.67
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	P-value	0.185	0.838

tribution, the F-test for speed variance, and the t-test for mean speed for each intersection approach.

Table 4 shows the results of the Kolmogorov–Smirnov normality test of speed distribution. The Kolmogorov–Smirnov Z is computed from the largest difference (in absolute value) between the observed and theoretical cumulative distribution functions. This goodness-of-fit test here is to test whether the speed data could reasonably have come from the Normal distribution ($P > 0.05$) or not ($P < 0.05$). It was found that all speed distributions at four approaches for both field and simulator studies followed normal distributions at the 0.05 significance level.

Table 5 shows the results of the F-test and the t-test for variance and mean comparisons, respectively. According to the F-test results, the speed variances in driving simulator were not significant different from those in field at the approaches of 434NB ($P = 0.120$) and 434SB ($P = 0.219$). However, the speed variances in driving simulator were statistically larger than those in field at the approaches of 50EB ($P = 0.001$) and 50WB ($P = 0.004$). Based on the variance type (equal or unequal), respective t-test statistic values were looked upon for mean comparison at each approach. From Table 5, there were no significant differences in mean speed between simulator and field at approaches 434NB ($P = 0.940$), 434SB ($P = 0.173$), and 50EB ($P = 0.491$). But the operating speed at the approach of 50WB was marginally faster in driving simulator than in field ($P = 0.051$).

Furthermore, the ANOVA result (see Table 6) shows that the factors of driver age ($P = 0.000$), driver gender ($P = 0.028$), and intersection approach ($P = 0.012$) were significantly associated with the operating speed in the simulator experiment. It was found that the mean speed for males was slightly higher than females and there was a decreasing trend in speed, after the 20–24 age group, as the age increases (see Fig. 6a). According to a previous report that investigated drivers' speeding and unsafe attitudes and behaviors (Royal, 2003), males (34%) were more likely to pass other vehicles than females (27%); almost half of all drivers under age 30 admitted that they tended to pass other vehicles and the likelihood of this behavior drops significantly with age. Those driving patterns related to speed are illustrated in Fig. 6b, which shows the similar trends in speed distributions by gender and age to those found in the simulator experiment. This finding relatively validated the driving simulator in terms of speed on a gender and age basis.

3.2. Safety validation for rear-end risk at right-turn lanes

3.2.1. Driving simulator as a leading vehicle

When subjects drove the simulator as a leading vehicle at the right-turn lanes of the 434NB and 50WB approaches, the independent variables were measured to evaluate the rear-end risk, including the simulator's average deceleration rate after the driver started braking, average speed distribution along right-turn lanes, and non-fully-stop rate at the stop line.

It was observed that average deceleration rate was higher for the 434NB approach ($M = 1.80\,\mathrm{m/s^2}$; S.D. $= 1.20\,\mathrm{m/s^2}$) than that for the 50WB approach ($M = 0.80\,\mathrm{m/s^2}$; S.D. $= 0.65\,\mathrm{m/s^2}$) [Equal variance; $t(111) = 5.563$; $P < 0.001$]. Generally, a higher deceleration rate is more likely to lead to a rear-end crash.

Fig. 7 shows speed distributions along the right turning lanes of 50WB and 434NB. The X-axis of the figure shows the locations of the vehicle upstream of the stop line, and the Y-axis shows the mean speeds of all the subjects at the locations. It can be observed that the mean speeds were consistently higher along the 50WB right-turn lane than that along 434NB at locations 100 m, 80 m, 60 m and 20 m since

Table 6
ANOVA analysis for speed as dependent variable

Source	Type III sum of squares	d.f.	Mean square	F	Sig.
Corrected model	4380.998	8	547.625	8.829	0.000
Intercept	425167.063	1	425167.063	6854.665	0.000
Age	3619.429	4	904.857	14.588	0.000
Gender	302.077	1	302.077	4.870	0.028
Approach	688.477	3	229.492	3.700	0.012
Error	14390.018	232	62.026		
Total	518658.241	241			
Corrected total	18771.017	240			

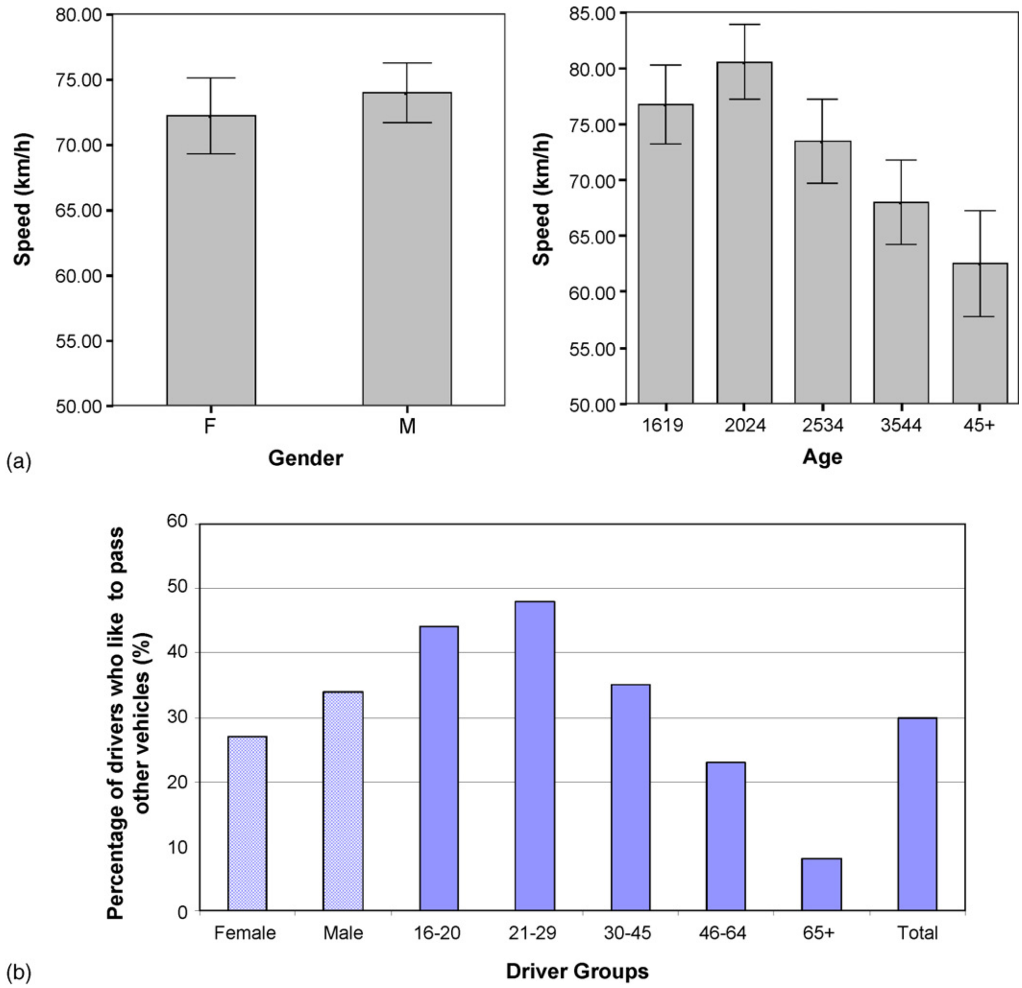

Fig. 6. Driving behavior patterns of speed by driver gender and age. (a) Speed distribution by driver gender and age in the driving simulator study. (b) Distribution of drivers who tend to pass most other drivers by gender and age in a survey study (Source: Royal, 2003).

the speed limit for 50WB (80.5 km/h) is higher than 434NB (72.4 km/h). However, at the stop line, the mean speed at 434NB (M = 18.38 km/h; S.D. = 8.90 km/h) was higher than that at 50WB (M = 14.68 km/h; S.D. = 6.04 km/h). This difference was statistically significant based on the t-test [Unequal variance; $t(104) = 2.649$; $P = 0.009$]. It means that when drivers make right-turns in a situation such as yielding the right of way for pedestrians or conflicting traffic from the other approaches, it is more likely to lead to an abrupt stop at 434NB than that at 50WB. Like most intersections in suburban areas, this intersection has few pedestrian activities and an actuated pedestrian signal. From Table 1, the intersection experienced only 3 pedestrian-involved crashes (1.8%) during the 4 years. However, since the pedestrian traffic volume is low at the intersection, the right-turn drivers are more likely to pay less attention to pedestrian activities. Therefore, if a right-turning driver still maintains higher speed at the stop line after signal change, a potential conflict with the pedestrian who just starts crossing the approach may cause the driver to make a sudden stop to avoid hitting the pedestrian. Generally, the leading vehicle's sudden stop creates the traffic condition of a rear-end crash occurrence.

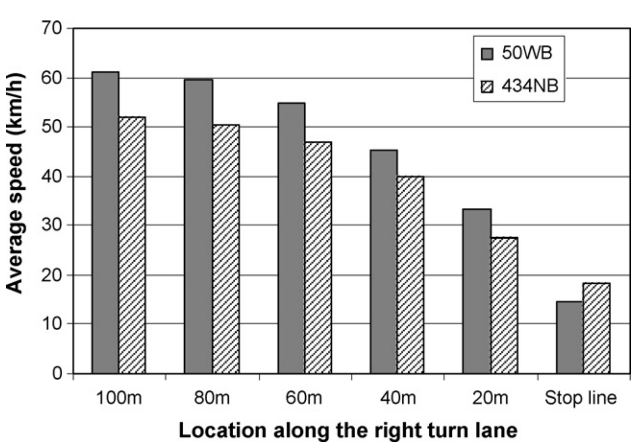

Fig. 7. Average speed distribution of a leading vehicle along the right-turn lanes.

Right-turn-on-red (RTOR) is permitted at all approaches for this intersection. A legal driving maneuver for such a situation would be fully stopping at the intersection first and then turning right if there is no conflicting traffic. A previous study indicated that 40% of drivers do not make a complete stop before executing an RTOR; among those who did come to a stop, only about

Table 7
Contingency table between intersection approach and full stop

Intersection approach	Full stop		Total
	No	Yes	
434NBL			
Frequency	49	11	60
Overall percent	41.18%	9.24%	50.42%
Row percent	81.67%	18.33%	
Column percent	59.04%	30.56%	
50WBL			
Frequency	34	25	59
Overall percent	28.57%	21.01%	49.58%
Row percent	57.63%	42.37%	
Column percent	40.96%	69.44%	
Total			
Frequency	83	36	119
Percent	69.75%	30.25%	100%

half did so voluntarily, whereas the other half were forced by traffic conditions to stop before turning (ITE, 1992). Based on observational data for more than 67,000 drivers at 110 intersections in three cities, Zegeer and Cynecki (1985) reported that 57% of drivers failed to make a full stop before turning right on red. Table 7 shows that overall 69.75% of the subjects did not fully stop at the stop line in the experiment, which displayed the general careless driving behavior of the subjects when they made right-turns during the signal change. Furthermore, it was found that the non-stop rate for 434NB (81.67%) was higher than that for 50WB (57.63%), which was statistically significant based on the Chi-square test [$\chi^2(1117) = 8.148$, $P = 0.004$]. For the 434NB right-turn lane, the distance between the stop line and the edge of the SR50 was relatively smaller (8.5 m) (see Fig. 5). Therefore, it requires less time to make a right-turn and drivers tend to quickly watch the traffic from other approaches and then turn without stopping. In contrast, the distance between the stop line and the edge of the SR434 is relatively larger (20.1 m). Hence, it requires longer time to make a right-turn so that drivers tend to drive slowly or stop at this area. The drivers who did not stop fully at the stop line could make a sudden stop in emergency situations, such as yielding the right of way for pedestrians or conflicting traffic from the other approaches, so as to increase the risk of rear-end collision with the following vehicles. This explanation can be supported by a previous study that investigated the effect of the distance from the stop line to the intersection on the RTOR behavior (Zegeer and Cynecki, 1986). It was found that offsetting the stop line, moving the stop line of adjacent stopped vehicles back from the intersection by 1.8–3.0 m (6–10 ft), was effective in providing better sight distance to the left for RTOR motorists. It also reduced the RTOR conflicts with other traffic and resulted in more RTOR vehicles making a full stop behind the stop bar.

By taking average deceleration rate, non-fully-stop rate, and right-turn speed as surrogate measures for the rear-end risk, it can be concluded that the driving simulator experiment reflected that drivers' right-turn behaviors were more risky at the 434NB approach than at the 50WB approach. Therefore, the driving behavior comparison between the two locations in the simulator is consistent with the crash history analysis.

3.2.2. Driving simulator as a following vehicle

When subjects drove the simulator as a following vehicle to make right-turns, the leading vehicle would make a sudden brake with a high deceleration rate [6.4 m/s^2 (21.06 ft/s^2 or 0.65 g)] at 50 m away from the stop line after the yellow change, which may lead to the rear-end crash occurrence. It was observed that there were more rear-end crashes that occurred in the 434NB right-turn lane than in the 50WB right-turn lane (9 versus 2). Based on the Z-proportion test, the rear-end probability (9/59 = 0.153) at the 434NB right-turn lane was significantly higher than that (2/60 = 0.033) at the 50WB right-turn lane ($Z = 2.24$; $P = 0.025$).

Table 8 shows the descriptive statistics of the other independent variables. The results show that the following speed at the 50WB right-turn lane ($M = 46.13$ km/h; S.D. = 3.35 km/h) was slightly higher than that at the 434NB right turn lane ($M = 44.41$ km/h; S.D. = 4.39 km/h) [Equal variance; $t(1117) = 2.411$; $P = 0.017$]. This result can be explained by the fact that the speed limit for the 50WB approach is higher than the 434NB approach. Furthermore, It was found that the average following distance at the 434NB right-turn lane ($M = 30.19$ m; S.D. = 13.43 m) was significantly shorter than that at the 50WB right-turn lane ($M = 35.58$ m; S.D. = 13.41 m) [Equal variance; $t(1117) = 2.191$; $P = 0.030$]. For the average deceleration rate, there is no significant difference found between the 434NB and 50WB right-turn lanes [Equal variance; $t(1117) = 0.693$; $P = 0.490$].

For the intersection geometry design, the length of right-turn bay in 50WB (200 m) is considerably larger than that in 434NB (60 m). Such a long right-turn lane in 50WB may help drivers prepare a turn maneuver much earlier than in 434NB, which explains why subjects kept relatively larger distances from the leading vehicles. Generally, a larger following distance can provide a driver enough reaction time to recognize a hazardous situation and make a stop decision. The shorter following distance in the 434NB right-turn lane directly contributes to the higher probability of rear-end occurrence observed in the experiment. Using the driving simulator as a following vehicle, the experiment results displayed the similar rear-end crash trend at the intersection compared to the crash history analysis.

4. Discussions and conclusions

Through carefully constructing geo-specific database for a signalized intersection in the driving simulator, this simulator validity study focused on investigating if the driving simulator can be developed as a test tool to assess traffic safety at signalized intersections. The validation research consisted of two aspects: speed measures and safety surrogate measures.

Comparing speed data observed from the field to those in the simulator experiment, the study showed that both follow normal distributions and have equal means for each intersection approach at the 0.05 significance level, which validated the driving simulator in terms of absolute validation. The findings are consistent with the previous research done by Kaptein

Table 8
Descriptive statistics of independent variables

Approach	N	Variable	N	Mean	S.D.	Minimum	Maximum	Range
434NB	59	Speed (km/h)	59	44.410	4.387	30.167	53.285	23.118
		Following distance (m)	59	30.191	13.43	11.071	92.515	81.444
		Average deceleration rate (m/s^2)	59	4.848	2.407	0.678	8.108	7.430
50WB	60	Speed (km/h)	60	46.133	3.348	36.889	58.598	21.708
		Following distance (m)	60	35.582	13.409	13.211	72.287	59.076
		Average deceleration rate (m/s^2)	60	4.549	2.299	0.960	8.207	7.246

et al. (1996) and Bella (2005). Furthermore, it was found that the speed variances were equal for the lower operating speed locations but unequal for the two locations with higher operating speed; there was a trend that the speed measured in the driving simulator showed a larger variability than the field. The variance comparisons of the driving behavior measures between simulator and field were not reported in most previous studies. However, they may be very important validity parameters because the larger behavior variances in driving simulators would lead to a larger sample size for the experiment design in order to generate sound conclusions. The reason for the larger speed variances observed in the driving simulator is unclear and could be complicatedly associated with the graphic fidelity level of the geo-specific database, the physical fidelity level of the simulator components, and the subjects' psychological factors. Hence, the research on the driving behavior variability in driving simulators is suggested for further simulator validity studies. Additionally, the distributions of mean speeds by driver age and gender in the simulator experiment are similar to the previous analysis from drivers' speeding attitude survey (Royal, 2003). Therefore, the relative validity was well established for the speed performance on a basis of driver age and gender.

Although absolute validity of a driving simulator is important and attractive, absolute validity is not always achievable and necessary for traffic safety research since traffic crashes are uniquely related to effects of various independent variables, which are difficult to obtain in field measurements when a crash happens. Moreover, absolute safety validation by comparing a driving simulator to an instrumented car in a field test such as crash avoidance research is often too dangerous on the real roads. For the safety validation, this study mainly focused on the relative validity to evaluate if the difference in the rear-end risk propensities between experimental intersection locations is in the same direction as what was found in the crash history analysis. Since traffic crashes are rare events and cannot directly be measured in the driving simulator experiment, the subjects' critical driving behavior measures were used as safety surrogates to perform the validation analysis. A summary of the safety validation findings are illustrated in Fig. 8. When subjects drove the simulator as a leading vehicle to make right-turns during the signal change, they showed a higher deceleration rate, higher non-stop rate, and higher speed at the stop line at the higher rear-end risk location (the northbound right-turn lane), compared to driving at the lower rear-end

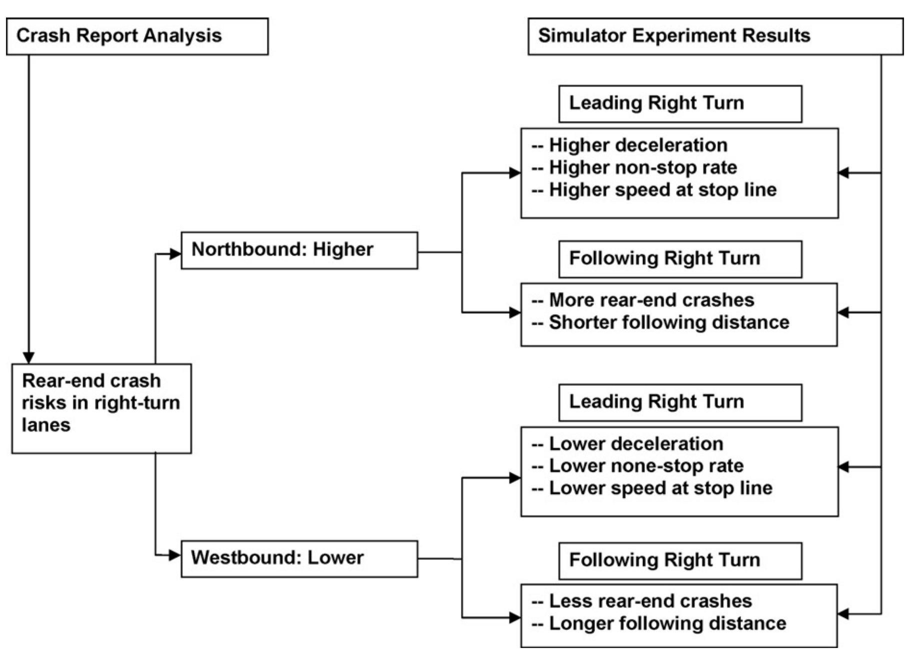

Fig. 8. Summary of the safety validation findings.

risk location (the westbound right-turn lane). Those behaviors are generally considered to be associated with the likelihood of rear-end crash occurrence. On the other hand, when subjects drove the simulator to follow a vehicle to make right-turns, a larger number of rear crashes occurred under a critical traffic situation at the northbound right-turn lane compared to driving at the westbound right-turn lane. The higher rear-end probability were attributed to the shorter following-vehicle distance at the northbound right-turn lane. The risk propensity discrepancy in those safety surrogates between the two locations can be explained by the intersection design features. At the westbound right-turn lane, the longer lane length is helpful for drivers to have an early awareness and preparation for the right-turn maneuver; the larger space between the stop line and the nearest highway edge can provide drivers a cushion function to lower the right-turn speed, deceleration rate, and non-stop rate.

On the whole, the simulator experiment results showed the similar speed behaviors to the field measures and reflected the crash history trend of the intersection. The research findings of this study support the concept that the driving simulator experiment in virtual reality can be utilized as a valid tool to identity traffic safety problems for signalized intersections in order to seek successful engineering countermeasures to lower crash rates for the high risk locations. The validation results in this study would be applicable to other studies using the simulator equipment with similar features to the simulator in this study, such as full-size cab, sufficient field of view, and motion base. However, drivers may have significantly different driving behaviors in the PC-base simulators or the full-size simulators without motion. Therefore, more parallel safety validity research is suggested for the different levels of simulators.

The method of using surrogate safety measures for simulator validity research provided a reference for the other similar simulator studies. Limited by the research scope, this study only tested rear-end crash in the driving simulator experiment. More safety issues and crash risk types such as red-light running, gap acceptance, and pedestrian-involved crashes are suggested to be conducted from the perspective of simulator validity. Furthermore, for the crash validity in this study, we mainly considered the simulator validity to test the crash risk associated with the design features of the intersection, but did not cover the crash validity on a basis of driver age and gender. It is suggested to conduct further simulator validity research related to driver characteristics in crash involvement.

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References

Abdel-Aty, M., Chen, C., Schott, J., 1998. An assessment of the effect of driver age on traffic accident involvement using log-linear models. Accid. Anal. Prevent. J. 30, 851–861.

Abdel-Aty, M., Keller, J., Brady, P., 2005. Analysis of the types of crashes at signalized intersections using complete crash data and tree-based regression. Transport. Res. Rec. 1908, 37–45.

Alexander, J., Barham, P., Black, I., 2002. Factors influencing the probability of an incident at a junction: results from an interactive driving simulator. Accid. Anal. Prevent., 779–792.

Alluisi, E.A., 1991. The development of technology for collective training: SIMNET, a case history. Hum. Factors, 343–362.

Bella, F., 2005. Validation of a driving simulator for work zone design. Transport. Res. Rec. 1937, 136–144.

Bella, F., Garcia, A., Solves, F., Romero, M.A., 2007. Driving simulator validation for deceleration lane design. In: The 86th Annual Meeting of the Transportation Research Board, Washington, DC, January.

Blaauw, G.J., 1982. Driving experience and task demands in simulator and instrumented car: a validation study. Hum. Factors 24, 473–486.

Dutta, A., Fisher, D., Noyce, D., 2004. Use of a driving simulator to evaluate and optimize factors affecting understandability of variable message signs. Transport. Res. Part F: Traffic Psychol. Behav. 7, 209–227.

Eddowes, E., Waag, W., 1980. The Use of Simulator for Training in-flight and Emergency Procedures. NATO Advisory Group for Aerospace Research and Development, Neuilly Sur Seine, France.

Federal Highway Administration (FHWA), 2004. Signalized Intersections: Informational Guide (Rep. No. FHWA-HRT-04-091). Washington, DC, USDOT, FHWA, 2004.

Godley, S., Triggs, J., Fildes, B., 2002. Driving simulator validation for speed research. Accid. Anal. Prevent. 34, 589–600.

Horberry, T., Anderson, J., Regan, M.A., 2006. The possible safety benefits of enhanced road markings: a driving simulator evaluation. Transport. Res. Part F: Traffic Psychol. Behav. 9, 77–87.

Institute of Transportation Engineers, 1992. Driver behavior at right-turn-on-red locations. Inst. Transport. Eng. J. 62 (4), 18–20.

Jamson, H., 1999. Curve negotiation in the Leeds Driving Simulator: the role of driver experience. Engineering in Psychology and Cognitive Ergonomics, vol. 3, pp. 351–358.

Jenkins, J., Rilett, L., 2005. Classifying passing maneuvers: a behavioral approach. Transport. Res. Rec. 1937, 14–21.

Kaptein, N., Theeuwes, J., Van Der Horst, R., 1996. Driving simulator validity: Some considerations. Transport. Res. Rec. 1550, 30–36.

Klee, H., Bauer, C., Radwan, E., Al-Deek, H., 1999. Preliminary validation of a driving simulator based on forward speed. Transport. Res. Rec. 1689, 33–39.

Lee, H., 2002. The validity of driving simulator to measure on-road driving performance of older drivers. In: The 24th Conference of Australian Institutes of Transport Research (CAITR 2002) University of New South Wales, Sydney, Australia.

McAvoy, D., Schattler, K., Datta, T., 2007. Driving simulator validation for nighttime construction work zone devices. In: The 86th Annual Meeting of the Transportation Research Board, Washington, DC, January.

Nilsson, L., 1993. Behavioural research in an advanced driving simulator-experiences of the VTI system. In: Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting, pp. 612–616.

Orlansky, J., String, J., 1977. Cost-effectiveness of flight simulator for military training. Use and Electiveness of Flight Simulators (IDA Paper No. P-1275), vol. I. Institute for Defense Analysis, Arlington, VA.

Rakauskas, M.E., Gugerty, L.J., Ward, N.J., 2004. Effects of naturalistic cell phone conversations on driving performance. J. Safety Res. 35, 453–464.

Royal, D., 2003. National Survey of Speeding and Unsafe Driving Attitudes and Behaviors: 2002. Findings Report, vol. II. National Highway Traffic Safety Administration. Report No. DOT HS 809 688, October, 2003.

Smith, D., Najm, W., Glassco, R., 2002. Feasibility of driver judgment as a basis for crash avoidance database development. Transport. Res. Rec. 1784, 9–16.

Salaani, M. K., Heydinger, G.J., 2000. Model Validation of The 1997 Jeep Cherokee For the National Advanced Driving Simulator. SAE Paper No.

2000-01-0700, SAE 2000 World Congress, Session, Vehicle Dynamics & Simulation, Detroit, MI, USA, March 2000.

Stamatiadis, N., Deacon, J., 1997. Quasi-induced exposure: methodology and insight. Accid. Anal. Prevent. 29 (1), 37–52.

Törnros, J., 1998. Driving behaviour in a real and a simulated road tunnel—a validation study. Accid. Anal. Prevent. 30, 497–503.

Zegeer, C.V., Cynecki, M.J., 1985. Determination of motorist violations and pedestrian-related countermeasures related to right-turn-on-red. Transport. Res. Rec. 1010, 16–28.

Zegeer, C.V., Cynecki, M.J., 1986. Evaluation of countermeasures related to RTOR accidents that involve pedestrians. Transport. Res. Rec. 1059, 24–34.