DSC North America 2003 Proceedings, Dearborn, Michigan, October 8-10, 2003 (ISSN 1546-5071).

ANALYSES OF TRAFFIC PARAMETERS RELATED TO LEFT TURN GAP ACCEPTANCE USING UCF DRIVING SIMULATOR

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ABSTRACT

The UCF driving simulator, housed in the Center for Advanced Transportation Systems Simulation (CATSS) laboratory, is a high fidelity simulator with access to an expansive virtual driving environment. It consists of a Saturn cab, motion base, scenario editor, operators console and Application Programmer Interface (API) for reading real-time data. The data includes driver inputs, namely steering wheel, accelerator and brake along with time stamped records of vehicle speed and position coordinates of the simulator and external vehicles. The sampling frequency is 30Hz.

This paper documents the simulator's use in an experiment designed to measure driver's gap acceptances for left turn maneuvers from a minor road to a major road with 25 mph and 55 mph major speed limits. In gap acceptance experiments, dependent measures focus on the following variables: critical gap acceptances, left turn time, average steering angle velocities, separation between vehicles, average acceleration rates of the simulator vehicle, and speed reduction and the decelerations rate used by major-road vehicles. By taking advantage of the driving simulator's extensive data collection capability and effective traffic management, experiments are easily performed to analyze drivers' behavior at intersections awaiting left turn maneuvers.

Keyword: UCF driving simulator, experiment design, gap acceptances, and traffic engineering.

INTRODUCTION

Driving simulators are currently used not only for training but also for research. They enable researchers to conduct multi-disciplinary investigations and analyses on a wide range of issues associated with traffic safety, highway engineering, Intelligent Transportation System (ITS), human factors, and motor vehicle product development (1). Several research studies (2,3) concluded that simulators are effective for use in projects related to sign detection and recognition distances.

The driving simulator housed in the Center for Advanced Transportation Systems Simulation (CATSS) laboratory is mounted on 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, steering wheel feedback, operator/instructor console with graphical user interface, sophisticated vehicle dynamics models for different vehicle classes, a 3-dimensional road surface model, visual database with rural, suburban and freeway roads plus an assortment of buildings and operational traffic control devices, and a scenario development tool for creating real world driving conditions. The output data include steering wheel, accelerator, brake, every car's speed and coordinates, and a time stamp. The sampling frequency is 30Hz.

This research concentrated on scenarios for gap acceptances for left turn maneuvers from a stopped position on a minor road to a major road with 25 mph and 55 mph speed limits. In gap acceptance experiments, dependent measures focus on the following variables: critical gap acceptances, left turn time, average steering angle velocities, separation between vehicles, average acceleration rates of the simulator vehicle, and speed reduction and the decelerations rate used by major-road vehicles. The objectives of this experiment are

- to determine the duration times of critical acceptable gaps in major-road traffic (for 25 mph and 55mph) that are accepted by the minor-road drivers;
- to evaluate the effect of major road traffic speeds on gap acceptance of left turners;
- to analyze drivers' behavior model at intersections, including the speeds, accelerations, and decelerations used by the minor-road vehicle and the following major-road vehicle when a gap in major-road traffic is accepted by the minor-road driver;
- to compare the results of the experiment to the road measurement data of a previous studies

BACKGROUND INFORMATION

According to the geometric design policy of the 1994 AASHTO Manual, Intersection Sight Distances (ISD) for left turn is based on models of the acceleration and deceleration behavior of the potentially conflicting vehicles. The section on Intersection Sight Distance has been completely revised in the 2001 AASHTO Manual, which is based on a time gap acceptance methodology (6). Gap is the time headway between two vehicles on the major road into which a minor-road vehicle may choose to turn. The gap-acceptance data are not only used to determine intersection sight distance, but also analyze capacity, queue length, and delay at unsignalized intersections (4,5). Gap acceptance scenarios are provided by AASHTO (2001) (6) for various levels of intersection control and the maneuvers to be performed. There are six scenarios (A to F) in the manual, and the one that pertains to this paper is defined as Case B1-Left turn from the minor road.

According to AASHTO (2001), the gap acceptance model is based on the assumption that time gap acceptance does not vary with approach speed on the major road. It adopted 7.5 sec as a constant value of critical gap acceptance for left turn from the minor road, independent of approach speed. An analysis of variance by Kyte et al. (5) found that the critical gap does not vary with approach speed. Harwood et al. presented field studies that were performed to determine the critical gaps and related traffic parameters of left turn maneuver for use in sight distance design. He also assumed that major road traffic speeds have no affect on gap acceptance (7). However, in a simulator experiment for left crossing from the major road (8), the velocity of the on-coming traffic was the variable that had the greatest effect on the median accepted gap size. This result corresponds to those of other previous studies involving gap acceptance, which have shown that drivers accept a smaller gap at higher approach velocities (9).

EXPERIMENTAL METHODOLOGY

Experiment Sample Size

Age and sex structure of the subject sample for the study is shown in Table 1. Every participant has a full Florida driving license with a minimum of 1-year driving experience. They were paid $20 for their participation.

Table 1: Age and sex structure of the subject sample

Age	18-55 years old	56-83 years old	Total
Male	25	10	35
Female	24	4	28
Total	49	14	63

Experimental Design

In the gap acceptance experiments a long straight undivided East-West two-lane collector was selected as the major road. Its length is around 9000 ft and lane width is 12 ft. A typical two way stop-controlled intersection (See Figure 1) was selected to test gap acceptances for Case B1-Left turn from the minor road. All subjects were tested in two scenarios, 25mph major road speed (Scenario A) and 55 mph major road speed (Scenario B).

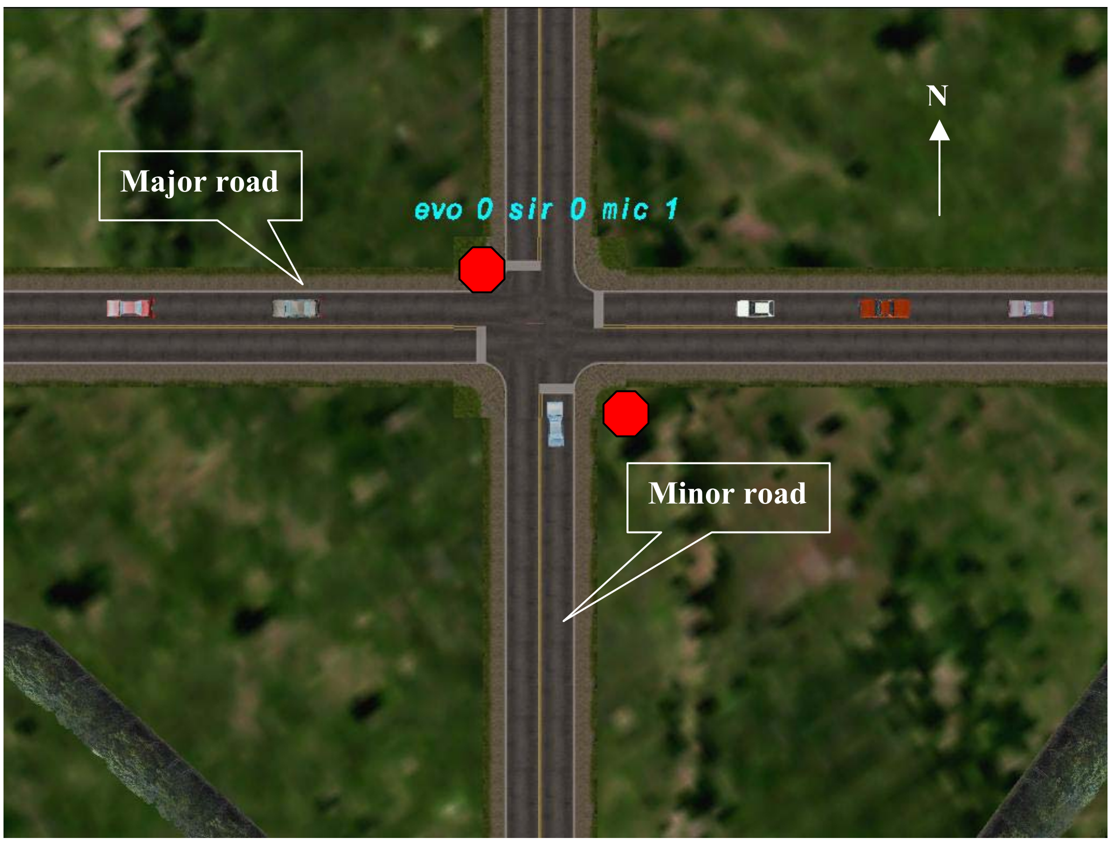

Figure 1: Four-leg Stop Controlled Intersection

A major challenge in designing this experiment was to assure that all drivers would experience a range of gaps which included their minimum acceptable gap in the real world. The disadvantage of traditional road data collection is that it is difficult to observe minimum gaps accepted by left turners. Furthermore the process is fairly long because the road traffic is uncontrolled. However, the road traffic can be precisely controlled in the driving simulator environment.

Oncoming traffic along the major road from the right was composed of two classes of intermingled gaps to make the traffic appear random. One gap classification was very small (less than 3 seconds) that were unlikely to be accepted by the subjects. The other class consisted of increasing gaps in which the subsequent gap was one second larger than the previous one. This assured that the selected gap would be close to the driver's minimum acceptable gap. The uniformly increasing gaps ranged in duration from 1 sec to 16 sec, a large enough variation to accommodate all drivers. This concept is illustrated in Figure 2.

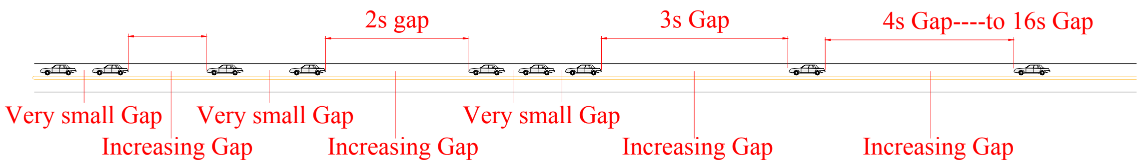

Figure 2: Design for Oncoming Traffic on the Major Road

Cars on the major road approaching the intersection are reclassified from “record vehicle” to “normal vehicle”. “Record vehicles” travel at constant speed whereas “normal vehicles” move intelligently along the major route. “Normal vehicles” attempt to travel at the design speed, however they decelerate or accelerate to keep a safe gap. Furthermore they are capable of passing slower moving vehicles ahead of them. Major road vehicles decelerate from the posted major road design speed, if necessary, to allow the simulator vehicle to negotiate the left turn. Consequently, the likelihood of collisions at a downstream point from the intersection was minimized, however collisions were still possible especially if the simulator vehicle entered the major road too slowly or selected an unusually small gap.

Experiment Procedure

Before the formal experiments began, all subjects were required to test-drive the simulator for a period of three minutes to become familiar with this system. After completing the familiarity course, the formal experiments began during which all subjects faced the same set of 2 driving scenarios, denoted A (25 mph) and B (55 mph) as shown in Table 3. The scenarios are presented as (A-B-A-B-A-B, or B-A-B-A-B-A) and repeated by each participant three times. Totally, there are six experiments, three As for 25 mph and three Bs for 55 mph. There is a short break (approximately 2 min) between scenarios.

In order to avoid driver bias, the participants were informed that the objective of the study was to assess the fidelity of the simulator and they should obey to the traffic laws and rules when driving the simulator.

DEPENDENT MEASURES

Data logging of all vehicles in the system occurred every 1/30-second. Logged variables included vehicle position (x and y coordinates) and speeds along with simulator driver inputs for acceleration, braking and steering.

Acceptable Gap

Gap is the time headway between two vehicles on the major road into which a minor-road vehicle may choose to turn. When the subject selects a gap to make a left turn, the acceptable gap is based on the distance (headway) between the lead and following vehicle at the time the following vehicle is about to cross the reference line shown in Figure 3. The accepted gap is the measured headway divided by the major road design speed.

Left Turn Time and Average Steering Angle Velocity

When the subject makes a left turn, the left turn time (LTT) interval is the time difference from the time at which the simulator begins to move, to the time at which it reaches the reference line shown in Figure 4. The average steering angle velocity (SAV) is equal to the total sum of the steering angle difference for every sample divided by the left turn time. The time interval for a left turn and the average steering angle velocity can be used to analyze the driver's behavior during the left turn.

Minimum clearance distance, speed reduction, and deceleration/acceleration rate

Clearance distance is the separation between the simulator vehicle while making a left turn and the following major-road vehicle. Deceleration by major-road vehicles to accommodate the merging simulator vehicle are measured. Average acceleration rates used by the left turning simulator vehicle during the period of the whole left turn maneuver are also recorded.

As the following car on the major road is approaching the intersection, the distance between the simulator and the following major-road vehicle gets smaller, until the minimum clearance distance between the two vehicles occurs. At about that time, the following car's speed is minimum and its speed reduction is greatest. Figure 5 illustrates the case where the minimum clearance distance is approximately 64 feet and the speed of the following car is 39.4 mph, nearly equal to that of the simulator vehicle (39.2 mph). As expected, the simulator vehicle has no effect on the speed of the leading car and therefore the leading car trajectory remains constant.

The values for minimum clearance distance, speed reduction, and deceleration rate are used to analyze the driver's behavior and further validate the simulator performance.

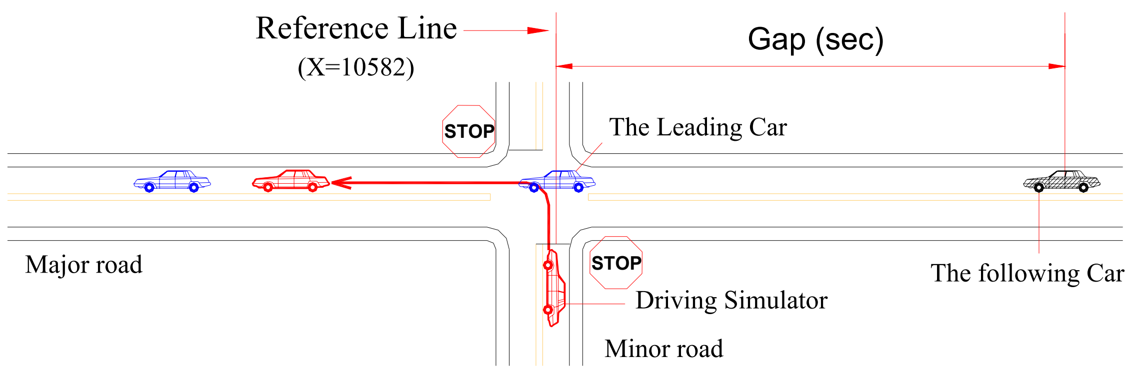

Figure 3: Data Record for Minimum Gaps

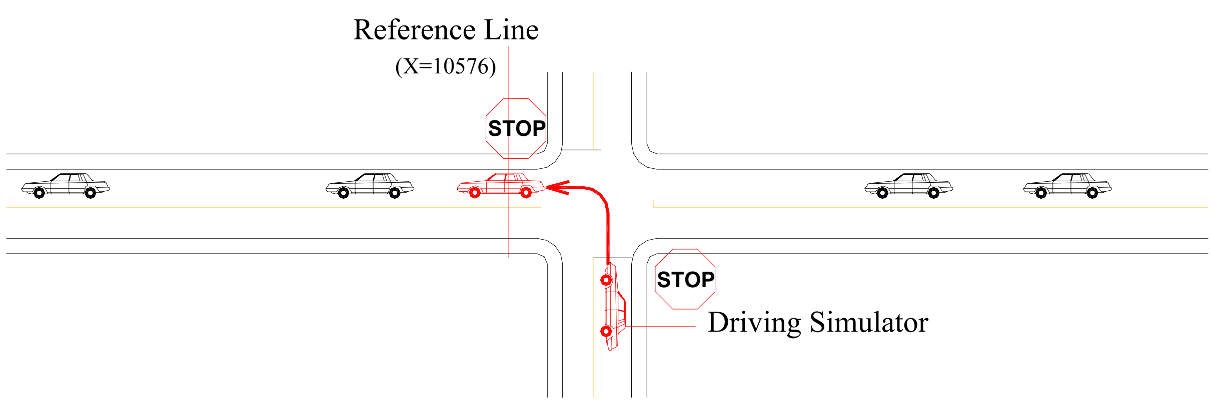

Figure 4: Data Record for Left Turn Time and the Average Steering Angle Velocity

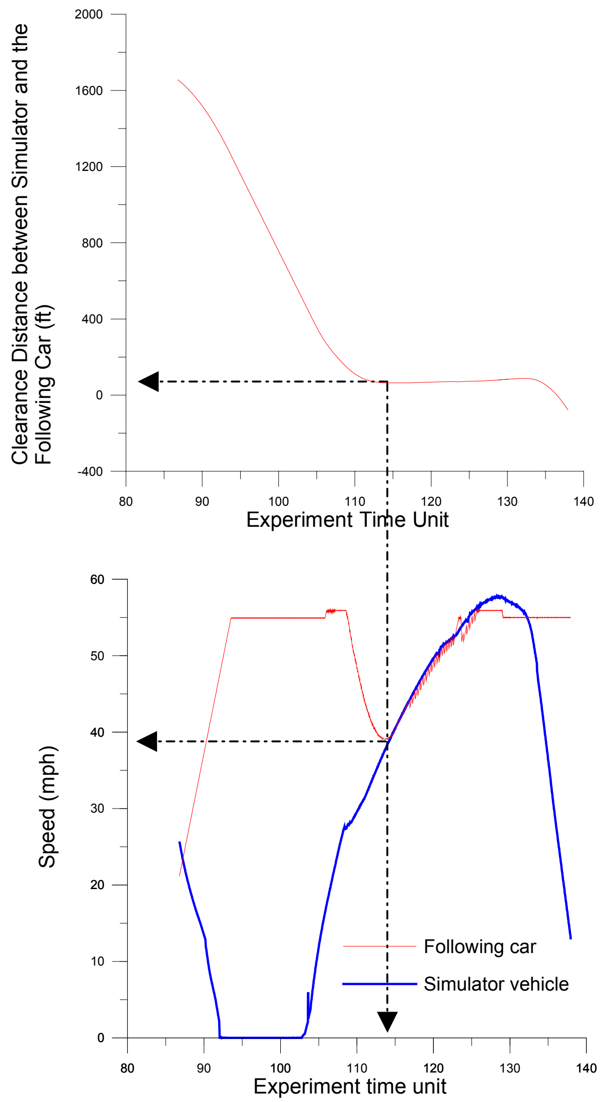

Figure 5: Relationship between clearance distance and speeds of the simulator vehicle and the following car

EXPERMENTAL RESULTS

Since all subjects have three choices to select gaps to make a left turn for both scenario A and B, average value of three gap acceptances and related traffic parameters was used for statistical analyses. The results for gap acceptance and related traffic parameters are shown in Table 2.

For the 25 mph speed major road traffic, the mean gap is 7.45 sec and its standard deviation is 2.1 sec. For the 55 mph speed major road traffic, the mean of gaps is 5.87 sec with standard deviation of1.44 seconds (See Table 2). Using a t-distribution, the mean difference in acceptable gap between the two speeds is 1.58 sec and the 95% CI for mean difference ranges from 1.24 sec to 1.92 sec. These results are significant at the 95 % confidence interval suggesting that gap acceptances of left turn are different for low and high traffic speeds on major road and drivers tend to accept smaller gaps facing higher approach velocities.

Table 2: Statistical analysis of gap acceptance and related traffic parameters

Scenario A_25 mph major road speed								
Parameter	GAP (sec)	MCD (ft)	SR (mph)	SRR (%)	ACC (ft/sec^2)	DEC (ft/sec^2)	LTT (sec)	SAV (rad/sec)
N	63	63	63	63	63	63	63	63
Mean	7.45	178.08	0.40	2	5.65	0.37	4.22	3.06
Median	7.02	185.53	0.04	0	5.61	0.00	3.98	3.00
Std. Deviation	2.10	60.60	0.80	3	1.71	0.68	0.91	0.80
Minimum	4.38	67.13	0.00	0	1.71	0.00	2.83	1.47
Maximum	13.70	342.19	4.22	17	9.02	3.41	6.71	6.33
Scenario B_55 mph major road speed								
Parameter	Gap (sec)	MCD (ft)	SR (mph)	SRR (%)	ACC (ft/sec^2)	DEC (ft/sec^2)	LTT (sec)	SAV (rad/sec)
N	63	63	63	63	63	63	63	63
Mean	5.87	81.06	13.26	24	4.53	3.54	4.19	3.00
Median	5.84	69.49	12.24	22	4.66	3.12	3.87	3.09
Std. Deviation	1.44	43.53	7.38	13	1.12	2.44	1.07	0.83
Minimum	3.00	44.32	0.00	0	1.54	0.00	2.76	1.27
Maximum	10.72	320.60	32.53	59	7.02	13.94	7.85	5.21

Notation:
GAP (sec): Gap time accepted by the driver
LTT (sec): Left turn time
SAV (rad/sec): Average steer angle velocity during left turn time
MCD (ft): Minimum clearance distance
SR (mph): Maximum speed reduction of the following car
SRR (mph): Maximum speed reduction rate of the following car
DEC (ft/sec^2): Deceleration of the following vehicle
ACC (ft/sec^2): Average acceleration during the whole left turn maneuver

According to the Logistic Regression method, when probability of acceptances is equal to 50%, the critical gap for 25 mph speed major traffic is 7.3 sec and the critical gap for 55 mph speed major traffic is 5.8 sec. Probability-gap formulas of the logistic regression for gap acceptances are shown as following:

For scenario A: $\ln [P/(1-P)] = 0.7862*X - 5.7504$ $(R^2 = 0.965)$
For scenario B: $\ln [P/(1-P)] = 1.2786x - 7.3895$ $(R^2 = 0.9885)$

Therefore, for low speeds the simulator results are fairly close to the 7.5 sec criteria recommended by AASHTO (2001). However, the gap acceptance criterion of AASHTO is a little conservative and safe enough for high speed highway operation.

The mean of left turn time for the 25 mph speed major road traffic was 4.22 sec and its standard deviation was 0.91 sec. For the 55 mph speed, the mean was 4.19 sec and its standard deviation was 1.07 sec. The mean of average steering angle velocities for the 25 mph speed was 3.06 rad/sec ranging from 1.47 rad/sec to 6.33 rad/sec. For the 55 mph speed, the mean was 3.00 rad/sec ranging from 1.27 rad/sec to 5.21 rad/sec (See Table 2). There was no significant difference found in left turn time and average steering angle velocity for low and high traffic speeds.

According to the experiment results (see Table 2), for the 25 mph major road speed (scenario A), the average MCD was 178.1 ft, with a range from 67.13 ft to 342.19 ft. The corresponding speed reduction was 0.4 mph ranging from

0 to 4.2 mph and the reduction rate 2% ranged from 0 to 17%. For the 55 mph major road speed (scenario B), the average MCD was 81.1 ft. The corresponding speed reduction was 13.26 mph. and the reduction rate was 24%. Thus, the observed speed reduction for scenario B is substantially larger than that for scenario A.

From the perspective of driving behavior, it demonstrates that drivers select larger gaps for low major road speeds. According to the field study (7), the reduction in speed by the major-road vehicle ranged from 0 to 80% of the vehicle's upstream speed, with a mean speed reduction of 32%. Compared to the field study, the speed reduction rates measured in the simulator experiment were smaller than road-measurement values.

For scenario A, the average acceleration of the simulator during the period of the whole left turn is 5.65 ft/sec^2, with speed ranging from 0 to 24.6 mph. For scenario B, it was 4.53 ft/sec^2 and a speed range from 0 to 41.76 mph. According to the field study (7), the observed average acceleration rate from a speed of 0-25 mph used by minor-road drivers in entering the major road was 4.9 ft/sec^2 for passenger cars and that from a speed of 0-40 mph was 3.6 ft/sec^2 for passenger cars. Compared to the field study, the simulator experiment results are slightly higher than road-measurement values. A possible explanation for this phenomenon is that the gas pedal of the simulator is smoother to press to its maximum acceleration limit than those of cars in real life. It also explained why the speed reduction rates of simulator experiment results are smaller than road-measurement values.

Table 2 showed that the average observed deceleration rate of the major-road vehicle over the distance traveled from its point of 25 mph major road speed to its point of minimum speed is 0.37 ft/sec^2, which is a very gentle deceleration rate. For 55 mph major road speed, the deceleration used by major road is 3.54 ft/sec^2. This implies that vehicles turning left on the minor road have little effect on the major road vehicles for lower major road speed, but do have an important effect on them for higher major road speeds. Gap acceptance research by Harwood (7) found average deceleration to be 2.2 ft/sec^2 for the major road speeds from 35 mph to 55mph. The reported deceleration rate (2.2 ft/sec^2) from the field study is between the values (0.37 ft/sec^2 and 3.54 ft/sec^2) obtained in the simulator experiments for 25mph major road speed and 55mph major road speed

CONCLUSIONS

There were 75 subjects taking part in the simulator experiments. Due to driving simulator sickness, about 10% of the younger male subjects and 20% of the younger female subjects were unable to complete the experiment. About 10% of the older male subjects and 40% of the older female subjects could not complete the experiments.

TABLE 3-T-test for scenario A_25 mph and scenario B_55 mph

Parameter	Scenario A				Scenario B				Mean Difference		
	N	Mean	95% CI		N	Mean	95% CI		Mean	95% CI	
			Lower	Upper			Lower	Upper		Lower	Upper
GAP	63	7.45	6.92	7.98	63	5.87	5.50	6.23	1.58	1.24	1.92
LTT	63	4.22	4.00	4.45	63	4.19	3.92	4.46	0.03	-0.17	0.24
SAV	63	3.06	2.86	3.26	63	3.00	2.79	3.20	0.06	-0.07	0.20
MCD	63	178.08	162.81	193.34	63	81.06	70.09	92.02	97.02	80.05	113.98
SR	63	0.40	0.20	0.60	63	13.26	11.40	15.12	-12.86	-14.74	-10.98
SRR	63	0.02	0.01	0.02	63	0.24	0.21	0.27	-0.22	-0.26	-0.19
DEC	63	0.37	0.20	0.54	63	3.54	2.93	4.16	-3.17	-3.83	-2.52
ACC	63	5.65	5.22	6.08	63	4.53	4.25	4.81	1.12	0.76	1.48

Simulator experiment results showed that the critical gap for the 25 mph speed major traffic is 7.31 sec and the critical gap for the 55 mph speed major traffic is 5.78 sec. According to the Paired T-Test comparison, there is a significant difference between values of gap acceptances for the 25 mph speed major traffic and the 55 mph speed major traffic. Simulator experiments testified that speed is an important factor to affect driver's gap acceptances. In addition, the driver's left turn maneuver for the 25 mph major road speed is very different from that for the 55 mph major road. The major road speeds have an apparent effect on the following traffic variables, as highlighted in Table 3: gap acceptance, minimum clearance distance, maximum speed reduction and deceleration of the following vehicle, and average acceleration during turn-driving average acceleration during the whole left turn maneuver. On the one hand, drivers making left turn to lower speed major road tend to select larger gaps, use smaller turn-driving but bigger straight-driving acceleration, and try to keep further separation from the following vehicle on the major road. On the other hand, for higher major road speed, drivers on the major road would use higher deceleration rate and reduce more speed to accommodate the turning vehicle.

The simulator experiment testified that its deceleration model is valid. However, the simulator experiment results of acceleration rates were slightly higher than road-measurement values, and the corresponding speed reduction rates used by the following car were smaller than road-measurement values. The possible reason to explain the phenomenon is that the gas pedal of the simulator is smoother to press to its maximum acceleration limit than that in real cars. Therefore, the larger acceleration rate the minor road vehicle used, the smaller major road vehicle speed reduced. The gas pedal's fidelity needs to be improved.

According to experiences of this simulator experiment, the design method also can be used to analyze other similar ISD researches, such as right turn from the minor road and crossing maneuver from the minor road.

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