Effects of Intersection Field of View on Emergent Collision Avoidance Performance at Unsignalized Intersections: Analysis Based on Driving Simulator Experiments

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Abstract

Proper intersection sight distance (ISD) can effectively lower the possibility of intersection accidents. AASHTO (2011) provides a series of recommended dimensions of intersection sight triangles for uncontrolled and stop/yield-controlled intersections. However, in reality although the actual intersection design for unsignalized intersections satisfies the requirements of sight distance and clear sight triangle in AASHTO's guideline, there are still a large number of crashes occurring at unsignalized intersections for drivers running stop/yield signs or failing to slow down. This paper presents a driving simulator study on pre-crash at intersections under three intersection field of view (IFOV) conditions. The aim was to explore whether better IFOVs at unsignalized intersections improve their emergent collision avoidance performance under an assumption of valid ISD design. The experimental results show drivers' ability to identify potential hazards to be significantly affected by their IFOVs. As drivers' IFOV improved, drivers were more likely to choose braking actions to avoid collisions. Better IFOVs were also associated with significant increases in brake time to intersection, and significant reductions in deceleration rate and crash rate, thus leading to a lower risk of traffic crash involvement. The results indicate that providing a better IFOV for drivers at intersections should be encouraged in practical applications in order to improve drivers' crash avoidance capabilities.

Keywords: Intersection Field of View; Collision Avoidance Behavior; Unsignalized Intersection; Crash Risk; Driving Simulator

1. Introduction

Intersections are the key components of road networks but have the potential for vehicular conflicts. The possibility of these conflicts actually occurring can be greatly reduced through the provision of sufficient intersection sight distance (ISD). The drivers approaching an intersection should have an unobstructed view of the entire intersection in order to timely detect potential conflicting vehicle and permit the drivers to anticipate and avoid potential collisions [1]. Thus, each quadrant of an intersection should contain a triangular area free of obstructions that might block an approaching driver's view of potentially conflicting vehicles. These triangular areas are known as clear sight triangles and the dimensions of the legs of the sight triangles depend on the design speeds of the intersecting roadways and the type of traffic control used at the intersection.

According to the American Association of State Highway and Transportation Officials (ASSHTO) [2], there is generally no sight triangles needed for signalized intersections, apart from the sight distance requirements for Left-turning vehicles. AASHTO (2011) provides specific guidelines of sight distance design for clear sight triangle according to different types of unsignalized intersections, including no-control-device intersection, yield-controlled intersection, and stop-controlled intersection. The recommended dimensions of the clear sight triangle for desirable traffic operations where approaching-intersection vehicles or stopped vehicles in the minor road enter or cross intersections are based on assumptions derived from field observations of rational and legal driving behaviors.

In terms of traffic safety, even though the intersection design for sight distance requirement and clear sight triangle is satisfied for uncontrolled, or yield-controlled, or stop-controlled intersections, there are still some drivers on minor road running stop/yield sign frequently without stopping or slowing their vehicles when approaching the intersections [3]. Typically, these illegal behaviors result in angular collisions [4]. According to the national data from the US on the vehicles involved in crashes in 2012, there were 22.36% of all crashes occurred at unsignalized intersections. Statistics show that traffic crashes at stop-controlled intersections account for approximately 6.5% of the total, while for uncontrolled and yield-controlled intersections, they account for roughly 12.2% and 3.6%, respectively [5]. "Failure-to-stop/yield" crashes in the minor roads at intersections controlled by stop or yield signs are caused by distracted drivers or reckless drivers who are in hurry to speed through an intersection at a high speed or inadvertently disregard requirements to stop/yield to crossing vehicles on the major roads [3, 6]. These emergent conflict situations also occurred at uncontrolled intersections. Hence, an interesting question is whether the intersection sight distance designs (or clear sight triangle designs) based on the rational driving behavior assumptions are still sufficient in those illegal cases that the minor road drivers fail to slow down or stop at intersections. Most previous studies concur that good sight distance design can improve intersection safety [7~10]. However, it is unknown whether further enhancing drivers' intersection field of view (IFOV) at intersections could improve traffic safety under the assumption that the sight distance meets the current intersection design standards.

To reduce the ISD-related crash risk, it is critical to understand how drivers' IFOV at conflicting intersections impact emergent collision avoidance performance, which depends on each individual driver's judgment, capabilities, and response to conflicting vehicles in the emergent situation. Considerable efforts in the field of emergent collision avoidance have been devoted to analyses of the influence of the drivers age [11], gender [12], driving experience [13, 14], drug/alcohol use [15], physical impairment, distraction, driving environment [16, 17], collision avoidance warning devices [18~20] and warning time [21, 22]. However, another important factor—drivers' IFOV—has received only limited attention. Only a few studies have been conducted to investigate how driving behavior varies with restricted sight view owing to other vehicles' obstructions at intersections. For instance, Harb et al. [16] found that drivers faced with visibility obstructions are more likely to be involved in angle and head-on collisions because they are less likely to take corrective evasive actions. Moreover, in earlier research, Harb et al. [23, 24] also found drivers' brake reaction time tends to increase with reduced sight distance, giving them insufficient time to respond to emergent collisions at intersections.

It should be pointed out that no study to date has analyzed the effects of IFOV caused by the roadside constructions on collision avoidance behavior at intersections, possibly because of the difficulty of collecting data on such behavior in the field. There is thus an urgent need to examine the relationship between driving safety and emergent collision avoidance behavior under different IFOV conditions at conflicting intersections. Driving simulators are considered to be effective tools for exploring this relationship because they provide a safe environment in which to test drivers' emergent collision avoidance behavior [25]. In addition, driving simulator experiments allow researchers to efficiently collect data in real time and to easily characterize drivers' behavior when they encounter unanticipated emergent situations.

The main objective of the study is to examine whether better IFOV conditions at unsignalized intersections can further improve drivers' collision avoidance performance, given that the sight distance meets the current intersection design standards respectively for uncontrolled and yield/stop-controlled intersections. To achieve that objective, a simulator-based experiment was first conducted to investigate the changes in collision avoidance behavior under different IFOV conditions to obtain a better understanding of the relationships among such behavior, IFOV, and traffic safety. Drivers' collision avoidance behavior was then observed, with data on important driving behavior parameters (including the entry speed when approaching the intersection in the normal driving phase; collision avoidance maneuvers, brake time to a conflicting vehicle, dynamic speed adjustment, and deceleration in the collision avoidance phase; and crash likelihood resulting from the collision avoidance maneuvers) extracted and examined through analysis of Type Ⅲ tests using mixed model and logistic regression analysis.

2. Methodology

2.1 Apparatus/equipment

The experiment was carried out using the driving simulator at Beijing Jiaotong University (BJTU). The BJTU simulator, which is shown in Figure 1, is a high-performance, high-fidelity driving simulator with a linear motion base capable of operation with one degree of freedom. It comprises a full-size vehicle cabin (Ford Focus) with a real operation interface, environmental noise and shaking simulation system, digital video replay system, and vehicle dynamic simulation system. The simulated environment is projected at 300 degrees of a front/peripheral field view at a resolution of 1400 × 1050 pixels and left, middle, and right back mirrors. The software in the simulator lab allows for driving scenario design, virtual traffic environment simulation, and virtual road modeling.

a. Driving and Simulation System   b. Monitoring and Control System

Figure 1: The BJTU driving simulator

2.2 Participants

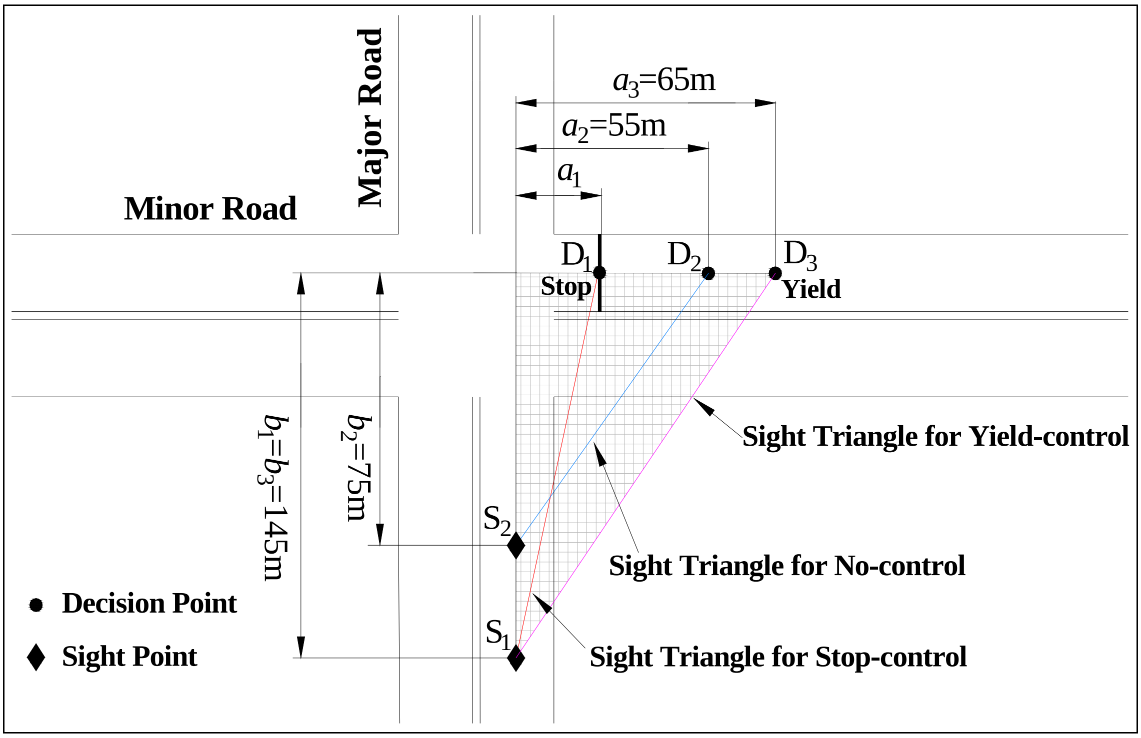
The experiment had a 3 (IFOV conditions) × 2 (gender) × 2 (professional status) mixed design with repeated measures on the factor of IFOV. Forty-five participants (24 men and 21 women) in two groups (23 professional taxi drivers and 22 nonprofessional drivers) were recruited from the local community and taxi companies. They were selected from the applicants who were interested in the recruitment advertisement we put on the Internet according to their personal information (age, gender, profession, years of driving, etc.). In order to balance the gender and profession distribution, the whole participants were consisted of 10 female nonprofessional drivers, 12 male nonprofessional drivers, 11 female professional drivers and 12 male professional drivers. The professional drivers selected for the experiment were full-time taxi drivers with an average mileage of 71 thousand kilometers per year and an average self-reported accident record of one per million kilometers. The non-professional drivers used their vehicles for the purpose of daily travel only. Their average mileage was 24 thousand kilometers per year, with an average self-reported accident record of eight per million kilometers. They ranged in age from 30 to 40, with an average age of 35 and a standard deviation (S.D.) of 3.04 years, although it should be noted that the age effect on driving performance was beyond the scope of this study. To be eligible for inclusion, participants had to hold a valid driver’s license and have at least three years of driving experience. Those with health problems that could affect driving behavior were excluded. The experiment lasted for about 30 minutes for each participant, who was compensated with RMB500 (approximately US$80).

2.3 Scenario design

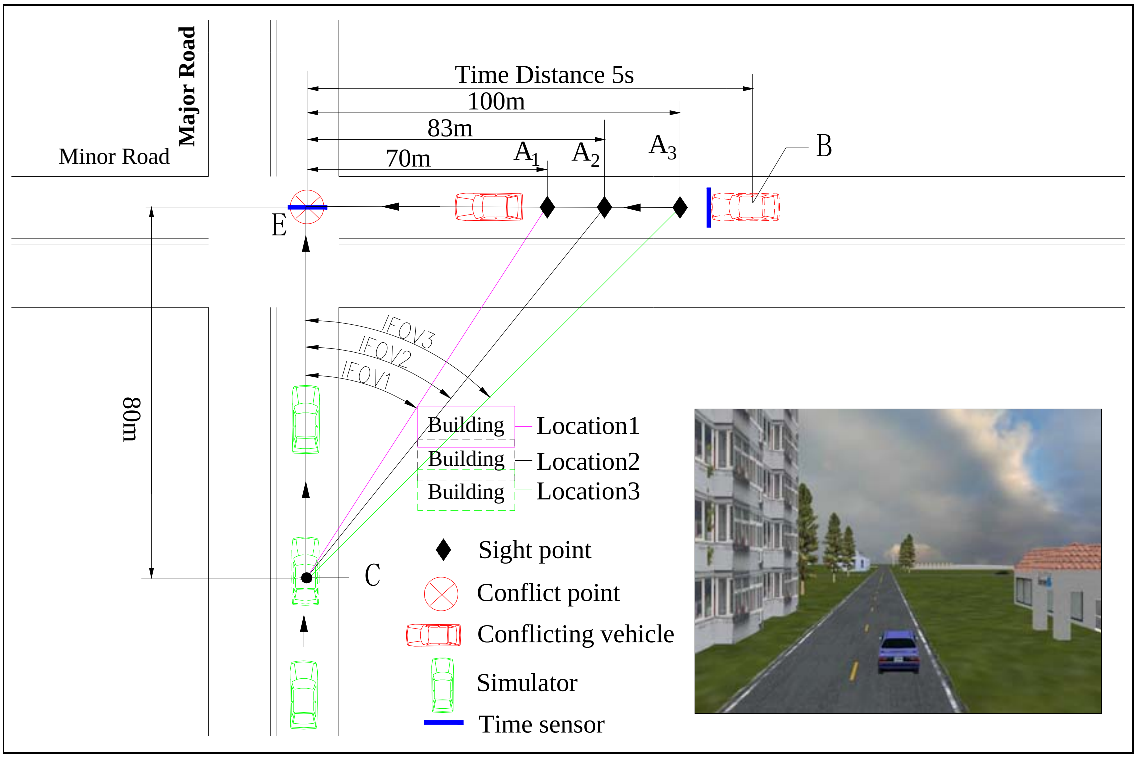
The current ISD guideline for unsignalized intersections is established from the observations to the rational driving behavior at different types of intersections. However, the traffic safety fact showed that even though the ISDs at the intersections satisfied the design guideline, numerous crashes occurred at unsignalized intersections due to the minor-road drivers running stop/yield signs or failing to slow down at the intersections [3~6]. Therefore, the purpose of this study is not to test ISD-related driving behavior at a certain type of intersection; rather, the key concept for scenario design in this study is that under the assumption of valid ISD design, a better IFOV condition at intersections may contribute to enhancing the collision avoidance performance for the drivers on the major road when encountering the illegal conflicting vehicles from the minor road.

Based on the above analysis, typical two-way two-lane uncontrolled intersections with the lane width at 3.5 m were created in the driving simulator system, and the speed limit was set at 80 km/h on the intersection’s major road and 60 km/h on the intersecting minor road. Figure 2-a shows the three clear sight triangles respectively for uncontrolled, yield or stop controlled intersection based on the ISD recommendations provided by AASHTO (2011) (note that the lengths of sight triangle legs were based on a design speed of 80 km/h on major road and 60 km/h on minor road). According to AASHTO's (2011) ISD guideline, at no-control intersections, the lengths of the legs (shown in Figure 2-a as dimensions a_2 and b_2) of sight triangular area are formed by the minimum required stopping sight distance (MRSSD) from the field observation that drivers typically reduce their speed to 50% of their mid-block operation speed when approaching a no-control intersection. For yield-control intersections, AASHTO (2011) provides sufficient sight distance for minor road vehicles to stop or cross safely based on a speed reduction to 60% of the mid-block running speed. For stop-control intersections, the measurement of distance a_1 depends on a marked stop line and the distance b_2 along the major road is determined by the design speed of major road and time gap accepted by minor-road vehicles.

According to AASHTO (2011) ISD recommendations for no-control intersections, the lengths of clear sight triangle legs should be 75 m for a design speed of 80 km/h and 55 m for a design speed of 60 km/h (shown in Figure 2-a). For the non-control intersections in this study, three IFOV conditions were designed as shown in Figure 2-b. For IFOV1 condition, the lengths of clear sight triangle legs are 80 m on major road and 70 m on minor road, which satisfy the basic ISD requirement for non-control intersection. Based on IFOV1, the intersection angles of IFOV2 and IFOV3 conditions were increased by 5º successively. These different IFOV conditions were realized by moving the location of a building (location-1, location-2, and location-3) at the corner of the intersection along the major road. Thus, the drivers from the major road (i.e., at Points C) can have a wider horizontal view (i.e., to Points A1, A2, and A3) as drivers' IFOVs increase. The design of these three IFOV conditions is to explore whether better intersection field of view would further improve drivers' collision avoidance behavior at unsignalized intersections even though the sight distance has met the current intersection design standards.



a. Intersection sight triangle for different types of traffic control



b. Emergent pre-crash scenario design

Figure 2: Sketch of simulator experiment

A time-to-collision (TTC) sensor was used to realize the emergent scenario of pre-crash between the simulator vehicle on the major road and a conflicting vehicle approaching the intersection from the minor road simultaneously. The TTC sensor triggered the event of the conflicting vehicle approaching the conflict point at a constant speed when the simulator vehicle neared the intersection. In such a situation, drivers have to engage in emergent collision avoidance maneuvers to avoid a collision. To create such a kind of emergency, the conflicting vehicle was designed to approach the intersection at a constant speed of 72 km/h. The distance from the conflicting vehicle's initial position (i.e., Point B) to the conflict point (i.e., Point E) was set at 100 m. Accordingly, the time duration from the conflicting vehicle's initiation of movement to arrival at the conflict point was 5 s. Therefore, the time value of the TTC sensor was set at 5 s. As shown in Figure 2-b, when the simulator vehicle arrived at a point, at which the time distance to Point E was 5 s, the conflicting vehicle at Point B was triggered to approach the intersection at 72 km/h. If the simulator vehicle driven by a participant continued at its current driving speed with no change, it collided with the simulated conflicting vehicle at Point E.

2.4 Experimental procedure

Upon arrival at BJTU, participants completed a short questionnaire, giving their name, gender, age, profession, annual driving mileage, and other information. Prior to the formal experiment, they conducted a practice drive of at least 10 min in a trial scenario to familiarize them with the driving simulator operation and driving environment. During this practice run, participants were advised to adhere to traffic laws and try different basic driving maneuvers such as acceleration, deceleration, braking, and right/left turns. They were also notified that if they felt motion sickness or any other kind of discomfort, they were free to quit the experiment at any time. After a five-minute break, participants needed to perform three sets of formal experiments in different IFOV conditions in a random sequence to eliminate the experiment order effect. Each experiment included the same rural-environment road network that composed of a series of typical two-way two-lane cross intersections while among these typical intersections there was only one intersection randomly assigned with a certain IFOV condition to test driving behaviors varied with IFOV. In each experiment, drivers should complete the whole road network driving unless they felt any discomfort. An emergent pre-crash scenario is a small-likelihood event in reality, and drivers are unlikely to encounter one emergent conflict after another in a short span of time. Hence, to discourage participants from speculating about the experiment's purpose and to minimize their adaptability to repeated collision avoidance tests, at least 10 minutes of normal driving in a typical rural traffic environment were inserted between each two sets of experiments.

2.5 Dependent measures

During the experiments, raw data on driving behavior were sampled at 60 Hz. One hundred and thirty-five datasets resulted from the three rounds of experiments under the three IFOV conditions. The measured parameters extracted from the raw data include the entry speed (ENS) of the simulator vehicle approaching the intersection in the normal driving phase; collision avoidance maneuvers (CAM), brake time to intersection (BTI), dynamic speed adjustment (DNS), and deceleration (DEC) in the collision avoidance phase; and crash rate

(COR) at the intersection. The dependent variables are defined as follows:

- ENS (km/h): The vehicle's instantaneous speed at a distance of 100 m from the conflict point.
- CAM (NCA = 0; ACA = 1; DCA = 2): Drivers' maneuvers to avoid collision with a conflicting vehicle. The CAMs were classified into three types: deceleration for collision avoidance (DCA), acceleration for collision avoidance (ACA), and no collision avoidance action (NCA), NCA means drivers keeping a relatively constant speed after a conflicting vehicle had been triggered.
- BTI (s): The time distance from the driver starting to brake to his/her arrival at the intersection conflict point.
- DNS (km/h): Each driver's average operation speed in each 5-m interval within the 100-m distance scope before the conflict point.
- DEC (m/s/s): The mean value of deceleration for vehicle speed adjustment to avoid a collision during the braking process, which was calculated by the following Equation (1).

$$DEC = (V_E - V_S)/T_b \qquad \text{Equation (1)}$$

in which, V_E represents the vehicle speed at the end of braking process; V_S represents the vehicle speed at the beginning of braking process; T_b represents the time duration of the braking process.

- COR (No = 0; Yes = 1): Whether the driver collided or not.

3. Results and discussions

The following analyses focus on the effects of driver's IFOV on their emergent avoidance performances. Previous studies have attempted to explain the effects of human factors like gender and profession in risky driving behavior and traffic accident involvement [12, 17, 26], thus the independent variables include IFOV levels (IFOV1, IFOV2, IFOV3), gender (Male and Female) and professional status (Professional and Nonprofessional). Considering for the experiment design described in this paper, a linear mixed model using type Ⅲ sum of squares was undertaken with IFOV levels as the within-subjects variable and the other two as between-subjects. In the subsequent statistical analyses, the hypothesis testing is based on a 0.05 significance level.

3.1 Entry speed and crash rate

3.1.1 Entry speed when approaching intersection in normal driving phase

Table 1 summarizes the basic statistics on ENS and corresponding Type Ⅲ tests show that none of the main effects or interactions was significant. However, male drivers were observed to have a slightly faster driving speed than their female counterparts (mean [M] = 67.82 km/h, S.D. = 10.04 km/h vs. M = 64.58 km/h, S.D. = 8.98 km/h), possibly because women drive more carefully than men [27]. Furthermore, the nonprofessional drivers had a higher ENS than the professional drivers (M = 67.98 km/h, S.D. = 10.08 km/h vs. M = 64.71 km/h, S.D. = 9.03 km/h). Professional drivers such as taxi drivers generally prefer a slower driving speed because the nature of their job requires them to keep to a low constant speed level and to make very frequent stops [28]. In addition, traffic rules/regulations and the rules of the organizations that employ them may also exert effects on these drivers' speed [29].

3.1.2 Crash rate

Table 2 presents the basic statistics on the collision results. More than a third (34.07%) of drivers failed to avoid a collision with the conflicting vehicle at the intersection, with male drivers having a higher COR than their female counterparts (37.50% vs. 30.16%) and nonprofessional drivers having a higher such probability than their professional counterparts (37.88% vs. 30.43%). There was a clear trend for COR to decrease as IFOV improved: i.e., COR was 51.11% for IFOV1, 31.11% for IFOV2 and 20.00% for IFOV3.

To determine drivers' COR quantitatively, a logistic regression model was developed to identify the variables that had a significant effect on such COR. A binary value was employed in the logistic regression analysis to predict COR (non-collision was assigned a value of zero, and collision a value of one). The logistic regression technique is widely adopted in estimating the effects of risky driving on COR [30~32].

The parameter estimates of the logistic regression models for COR are shown in Table 3. The model results indicate that COR is significantly affected by IFOV, although no significant effects are observed for the independent variables of gender and professional status. Compared to the condition of IFOV1, COR at conditions of IFOV2 and IFOV3 decreased by 57.3% and 76.5%, respectively. This finding suggests that the improvement of drivers' IFOV could be an effective method for reducing crash risk.

3.2 Collision avoidance behavior analysis

3.2.1 Collision avoidance maneuvers

Different drivers execute different maneuvers (DCA, ACA or NCA) to avoid collision with a conflicting vehicle when approaching an intersection. The basic statistical descriptions of these CAMs and the corresponding chi-square test results are given in Table 4. The results show the maneuvers to be significantly affected by different IFOV conditions ($p = 0.007$), but not the driver's gender or professional status. Nearly three-quarters (73.33%) of the participating drivers chose DCA, whereas just 7.41% chose ACA and 19.26% NCA. These results suggest that the majority of drivers considered deceleration to be the safest option for avoiding a collision with a conflicting vehicle when traveling across an intersection.

More female than male drivers engaged in DCA (77.78% vs. 69.44%), with the latter thus having a higher COR (30.16% vs. 37.50%). This result is in line with previous research showing male drivers to be more likely to engage in unsafe driving actions [33]. Further, the professional drivers were found slightly more likely to choose DCA (73.91% vs. 72.73%), whereas more nonprofessional drivers opted for NCA when approaching the intersection (21.21% vs. 17.39%). This result partially explains the higher COR recorded for nonprofessional drivers relative to their professional counterparts (37.88% vs. 30.43%). Figure 3 shows that the proportion of drivers in the DCA category increased from 53.33% to 84.44% and that COR fell from 51.11% to 20.00% as the IFOV improved from IFOV1 to IFOV3. The dramatic increase in the number of drivers decelerating to avoid a collision at a condition of IFOV3 may have lowered the crash potential because drivers are able to make a more timely response to an emergency situation at this IFOV3 condition relative to one of IFOV1. The implication is that drivers should be encouraged to engage in deceleration maneuvers to reduce the likelihood of a collision. A particularly interesting finding from Figure 3 is that the proportion of drivers in the NCA category was higher at the IFOV1 condition than that at the conditions of IFOV2 and IFOV3 (35.56% vs. 15.56% vs. 6.67%). This result indicates that the more restricted the IFOV is, the less likely drivers are to perceive the conflicting vehicle.

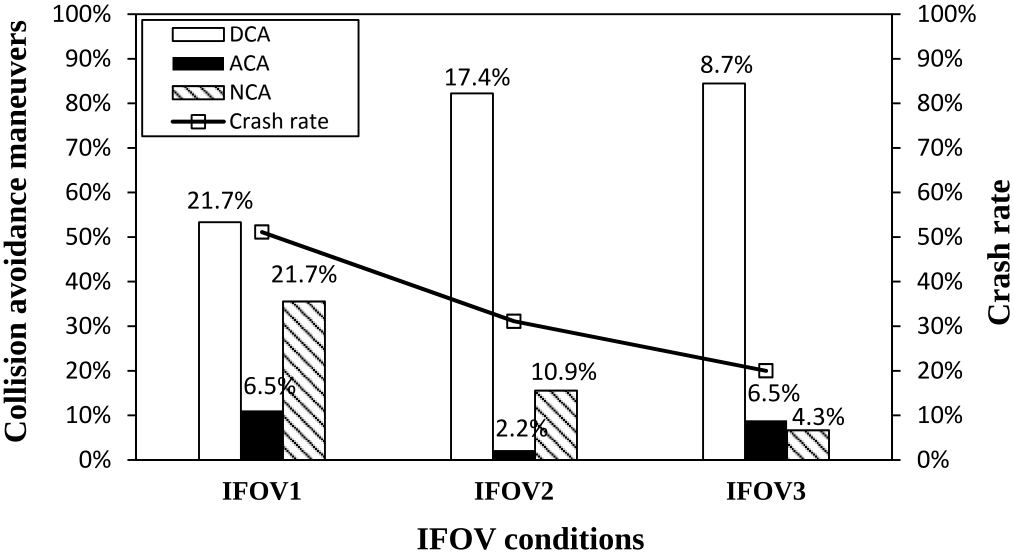


Figure 3: Relationship between CAMs and COR under different IFOV conditions (Note: the numbers on the histogram represent the crash rates resulted by different maneuvers)

Table 4 also reveals the collision occurrence ratio to vary with different CAMs. Among the drivers opting for DCA, just 22.22% collided with the conflicting vehicle, a much lower proportion than that for those opting for NCA and ACA (22.22% vs. 65.38% vs. 70.00%). According to the results in this experiment, it seems that deceleration maneuvers are the best, and acceleration maneuvers the worst way to avoid a crash at an intersection, but in actual circumstances, the selection of maneuvers may also depend on when it is initiated. The next step was to determine the basic mechanism in the process of emergent collision avoidance based on the sample of deceleration for collision avoidance.

3.2.2 Brake time to intersection

A summary of the basic statistics on BTI and the corresponding Type Ⅲ tests of fixed effects are reported in Table 5. It can be seen that IFOV levels ($F = 21.47$, $p < 0.01$) and professional status ($F = 5.60$, $p < 0.05$) have significant effects on BTI, whereas no gender or interaction effects are observed.

The nonprofessional drivers were observed to have a smaller BTI than the professional drivers (M = 2.18 s, S.D. = 1.27 s vs. M = 2.50 s, S.D. = 1.36 s), which is consistent with previous findings that experienced drivers are superior to inexperienced drivers in hazard perception [34], and implies that the former are more likely to pay attention to intersection safety and thus better able to take quick corrective action in the face of an unanticipated traffic event. Although the driver's gender exerted no significant effect on BTI, men braked slightly earlier than women (M = 2.45 s, S.D. = 1.35 s vs. M = 2.24 s, S.D. = 1.29 s), possibly because men generally have more driving experience than women [35].

Table 5 also shows the smallest BTI to be at a condition of IFOV1 (M = 1.33 s, S.D. = 1.04 s), followed by the conditions of IFOV2 (M = 2.31 s, S.D. = 1.18 s) and IFOV3 (M = 3.05 s, S.D. = 1.19 s). Figure 4 clearly shows that the mean BTI increases as drivers' IFOV improves. A wide driver horizon is usually associated with a larger IFOV, a situation that allows drivers to perceive the conflicting vehicle in advance and thus brake more quickly.

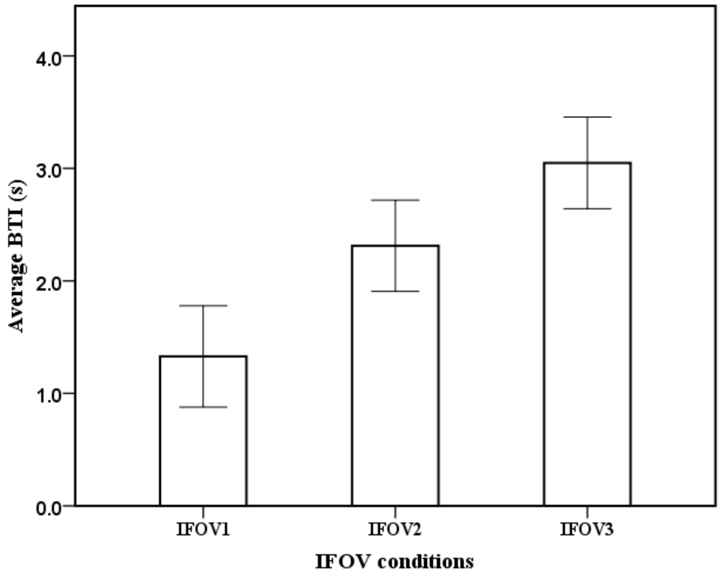


Figure 4: Distribution of average BTI in terms of IFOV condition (Note: the error bars represent a 95% confidence interval)

3.2.3 Dynamic speed adjustment and deceleration in collision avoidance phase

Figure 5 shows the DNS at each 5-m interval within the 100-m distance scope before the conflict point in the three IFOV conditions. It can be seen that drivers exhibit greater DNS at a condition of IFOV1 than at the conditions of IFOV2 or IFOV3. Table 6 presents the significant effects of IFOV levels on DNS during the distance from 60 m to the conflict point, as well as significant profession effects mainly observed during the distance of 70 m to 25 m from the conflict point. The Post Hoc Test (LSD) in Table 6 shows that for the three IFOV conditions, the difference between IFOV1 and IFOV3 appeared to be most significant for their effect on the DNS.

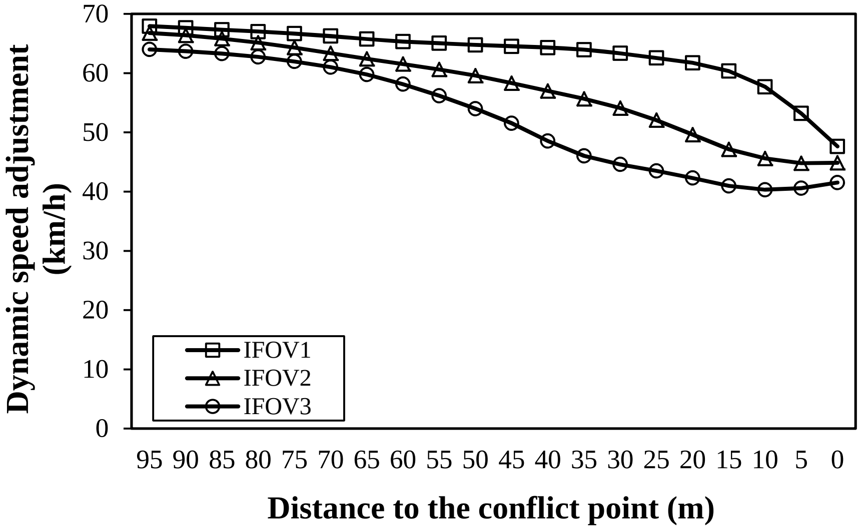


Figure 5: Distribution of DNS in terms of IFOV condition

Table 7 report the basic statistical descriptions of DEC and corresponding Type Ⅲ tests in Mixed model. It can be seen that DEC is significantly affected by IFOV ($F = 6.18$, $p < 0.01$) and gender ($F = 5.34$, $p < 0.05$), but the Type Ⅲ tests reveal no significant professional status or interaction effects. The average deceleration rate for female drivers is higher than that for male drivers (M = 3.87 m/s/s, S.D. = 2.03 m/s/s vs. M = 2.90 m/s/s, S.D. = 1.80 m/s/s). This observation explains the fact that the female drivers stepped on the braking pedal more heavily partially because of higher levels of driving stress and lower levels of taking risks of a collision [36~38]. Furthermore, it can clearly be seen that the average deceleration rate at a condition of IFOV1 (M = 4.49 m/s/s, S.D. =2.28 m/s/s) is higher than that at conditions of IFOV2 (M = 3.29 m/s/s, S.D. = 1.95 m/s/s) and IFOV3 (M = 2.77 m/s/s, S.D. = 1.49 m/s/s), suggesting that drivers reduce their deceleration rate as IFOV increases.

It can be seen from Figures 5 that drivers at the IFOV1 condition begin taking emergent deceleration actions about 15 m before the conflict point. It can be inferred from this observation that when drivers' IFOV is smaller, drivers drive at a constant speed as they near the intersection without perceiving the conflicting vehicle until they engage in emergent braking 15 m from the conflict point, thus leading to a greater deceleration rate. However, as the IFOV improves, drivers perceive the conflicting vehicle earlier and thus exhibit deceleration behavior about 60 m from the conflict point and approach the intersection with smooth deceleration action. The DNS curve at the IFOV3 condition also reveals an interesting phenomenon: vehicle speed increases slightly at a distance of 10 m from the conflict point, which indicates that drivers begin accelerating when they perceive the conflicting vehicle to have passed through the intersection.

3.3 Relationships among IFOV levels, collision avoidance behavior, and crash risk

Based on the DCA sample data (99 in total), Table 8 presents the results of correlation analyses of the variables of IFOV, ENS, BTI, deceleration rate, and COR. COR reflects the crash risk. Drivers' IFOV clearly has a significant effect on COR, and there is a negative correlation between these two parameters. Intuitively, if the IFOV is greater, COR declines, which indicates that IFOV at intersections exerts an influence on crash risk. However, driving behavior is often used to explain crash risk in the process of emergent events [39, 40]. Therefore, it was deemed important in this research to investigate the basic mechanism underlying the two parameters, and correlation analysis was further employed to analyze the relationships among IFOV, collision avoidance behavior, and crash risk.

Table 8 shows that IFOV has significant correlations with BTI, deceleration rate, and COR. It also shows that all of the parameters are significantly correlated with COR, although there is no significant correlation between deceleration rate and COR.

When approaching an intersection, different drivers may maintain a similar ENS that is not significantly influenced by their IFOV. However, ENS has a significant effect on COR, and the two parameters are positively correlated. In other words, if drivers in the normal driving condition adopt a higher ENS, the result may be a higher crash risk, as well as more severe damage and personal injuries [41~43]. Hence, ENS is an important determining factor in intersection accidents [44, 45]. Further, correlation analysis also shows ENS to be negatively correlated with BTI. In other words, drivers who maintain a high speed when entering an intersection are likely to take longer to depress the brake pedal, i.e., exhibit a small brake time to intersection, when an emergent crash occurs [20]. Research shows that drivers' gaze is increasingly constrained by an increase in driving speed, and drivers with a constrained range of focus are less likely to perceive the objects around them and thus more likely to exhibit delayed braking action in attempting to avoid an incipient crash [46].

Correlation analysis on BTI shows that it has a highly positive correlation with IFOV and a significant correlation with COR. Figure 6 shows the BTI distributions for drivers who involved collisions or not. It clearly illustrates that the BTI for collision cases (M = 0.89 s, S.D. = 0.68 s) is significantly smaller than that with non-collision cases (M = 2.70 s, S.D. = 1.19 s) according to the Type Ⅲ test ($F = 37.84$, $p < 0.01$). Among the drivers who failed to avoid collisions, the BTI mainly distributed between 0.5s ~ 1.5s, namely drivers are more likely to involve in collisions when BTI is smaller than 1.5s at unsignalized intersections. Accordingly, the time that drivers begin to brake plays an important role in analysis of intersection safety [47, 48]. In the current research, BTI increased significantly with an improvement in IFOV, rising from 1.33 s to 3.05 s (see Figure 7). The earlier the drivers begin to brake, the lower the likelihood of collision. Evans [49] showed that a fast brake reaction can reduce both the probability and severity of crashes. In this study, at a condition of IFOV3, drivers are able to perceive the conflicting vehicle in advance of reaching the conflict point and have more time to identify the emergent accident risk, which results in COR declining from 45.5% to 18.2%. Therefore, the crash risk is much lower for drivers with a condition of

IFOV3 than for drivers with conditions of IFOV1 or IFOV2.

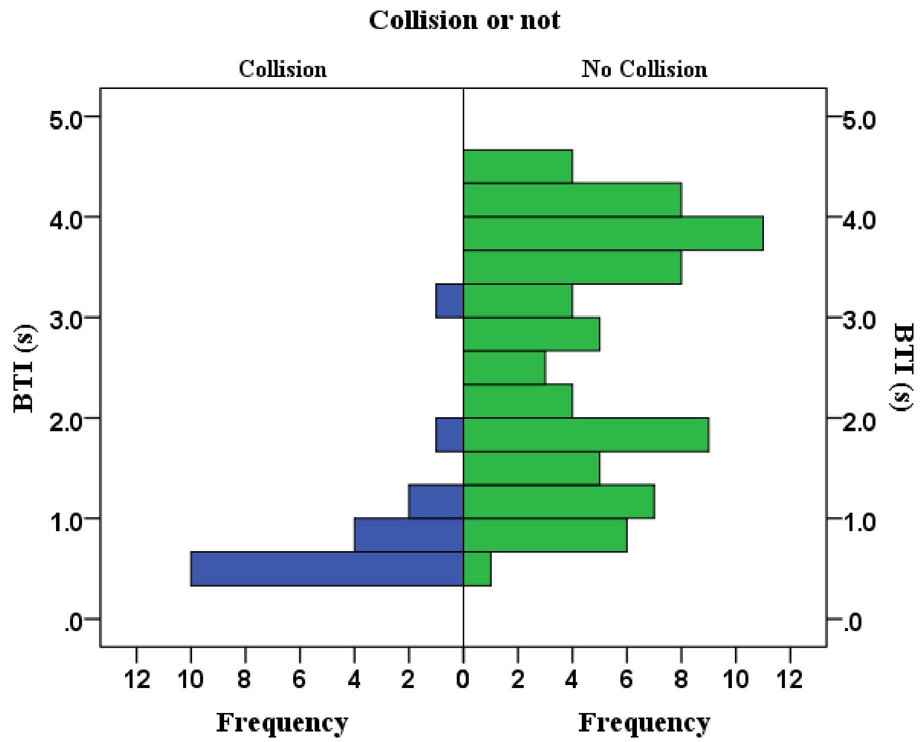


Figure 6: BTI distributions in terms of collision or not

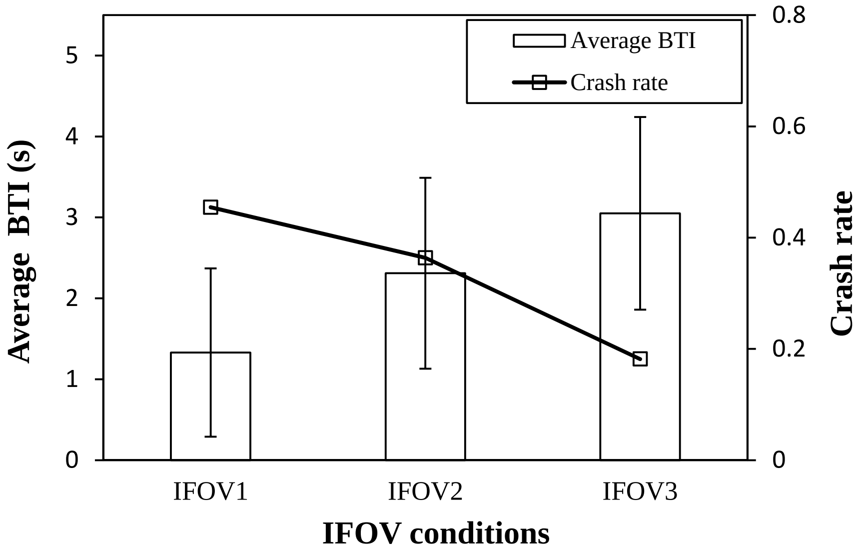


Figure 7: Relationship between average BTI and COR under different IFOV conditions (Note: the error bars represent a 95% confidence interval)

DEC represents the speed adjustment rate during the process of emergent collision avoidance, which demonstrates drivers' operational ability to control the vehicle, and can be applied to measure conflict severity [50]. Our correlation analysis reveals IFOV to be significantly correlated with the deceleration rate. Figure 8 shows that the greater the IFOV, the lower the average deceleration rate, and that COR reduces as the average deceleration rate decreases. Keay et al. [51] found that drivers who make a rapid change in their speed at a higher deceleration rate when approaching a potential conflict area are actually at greater risk of crash involvement. In the current study, it was found that drivers' average deceleration rate decreased from 4.49 m/s/s to 2.77 m/s/s as the IFOV improved from IFOV1 to IFOV3. Drivers with a better field of vision in the IFOV3 case who also displayed smooth deceleration behavior had a lower probability of collision with the conflicting vehicle and a lower crash involvement risk compared to those who engaged in urgent braking and rapid deceleration at a condition of IFOV1.

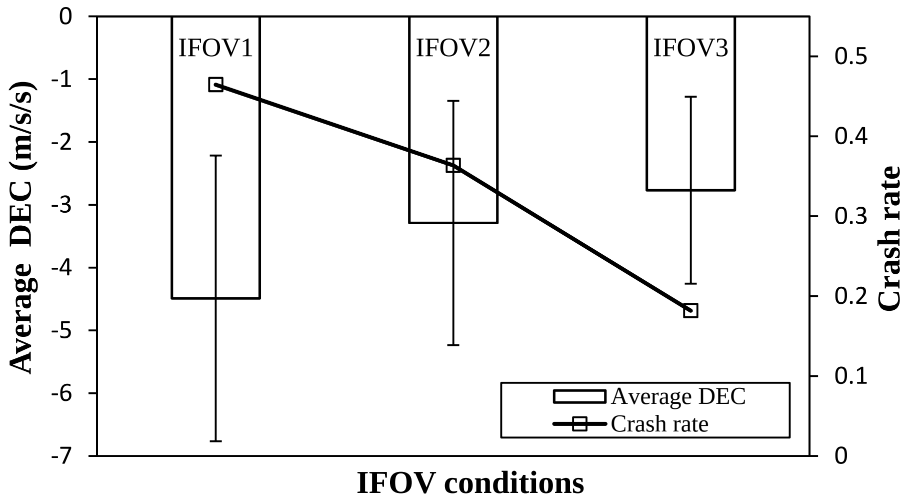


Figure 8: Relationship between average DEC and COR under different IFOV conditions (Note: the error bars represent a 95% confidence interval)

4. Conclusions

As previous studies have proved that good sight distance design can promote intersection safety, the paper further investigated whether better IFOV conditions at unsignalized intersections can further improve drivers' collision avoidance performance, given that the sight distance meets the current intersection design standards for unsignalized intersections. The high-fidelity driving simulator experiment reported herein confirms the positive effect of incremental improvement in drivers' IFOV on traffic safety at an unsignalized intersection, which can be reflected by significant changes in a series of collision avoidance behaviors and the collision avoidance results. The study's results indicate that as IFOV improved, drivers are more likely to choose braking action to avoid a collision and they also braked earlier in front of the intersection, and there are also significant reductions in drivers' deceleration rate and crash rate. In the scenarios considered, the crash occurrence ratios for the conditions of IFOV2 and IFOV3 were 57.3% and 76.5% lower than those for the IFOV1 situation. Correlation analysis shows that IFOV affects drivers' ability to identify potential hazards. Accordingly, drivers with insufficient IFOV tend to brake late because of their diminished ability to perceive the conflicting vehicle in an efficient and timely manner. They thus have less time and distance to decelerate and avoid an emergent accident when approaching the conflict point, thereby resulting in higher collision likelihood.

From the view of results analyses in this study, the ISD designs (or clear sight triangle designs) that satisfied the current intersection design standards in AASHTO are still not sufficient in those illegal cases that the drivers on the minor road fail to slow down or stop at intersections. In practice, project managers are very likely to adopt the smallest clear sight triangles that satisfy the minimum required intersection sight distance to minimize project costs. This study shows that smaller clear sight triangles can compromise intersection safety, and thus that the greater IFOV should be encouraged in practical applications, for example, by removing the low-cost buildings, unnecessary advertising board or billboard from the unsignalized intersections. Especially for the accident blackspots or intersections with higher traffic volume, the wide intersection field of view for drivers should be provided as much as possible. Additionally, drivers' gender and professional status may also exert effects on emergent collision avoidance behavior. For example, it was observed in this study that nonprofessional drivers have a significantly smaller brake time to intersection than professional drivers and that female drivers have a higher deceleration rate than male drivers.

The results reported in this paper further our understanding of emergent collision avoidance behavior at unsignalized intersections. We tested drivers under three IFOV conditions, and found that IFOV enhancement is an effective method of improving traffic safety. However, it should be mention that this viewpoint was concluded through a driving simulation experiment and there are still some general limitations and validation considerations for simulator experiments. One of the major problems is the simulator sickness, which occurs frequently with all driving simulators and particularly among older adult drivers [52]. Due to the simulator sickness symptoms, some participants are unable to continue using the simulator and are thus unable to complete the intended assessment tasks. Therefore, this study focused on young mature drivers (age from 30 to 40) in participants recruitment and encouraged the ones with sickness to quit the experiment at anytime they felt uncomfortable to avoid the sickness effect. Another concern with using driving simulators is the simulator validity. It should be mentioned that simulator validity is highly dependent on the specific simulator, task, and population under consideration [53, 54]. It is obvious that driving simulation is not real driving (especially in terms of risk) and subjects also knew that their driving errors would not affect their safety. However, we could not, from an ethical stand point, put the participants in a real driving situation with any potential collision risk and thus, driving simulator is a proper tool to be used when possible danger might occur in the experiment. In addition, even if there are some differences between results collected in a real driving situation and on simulated driving, numerous studies have proved that driving simulators provide an adequate representation of the real world [55~57] and particularly have a relative validity in driving performance studies [58]. Thus, if specific IFOV levels are recorded in future traffic crashes datasets, the authors strongly recommend statistical safety analysis to further calibrate the results of this study.

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List of Tables

Table 1: Descriptive statistical results for ENS

Variable	Classification	ENS			
		Mean(M)	S.D.	Min	Max
IFOV levels	**IFOV1**	67.19	7.88	50.66	84.03
	IFOV1-Male	69.42	7.17	56.28	84.03
	IFOV1-Female	64.65	8.05	50.66	77.82
	IFOV1-Professional	64.77	6.50	54.42	77.35
	IFOV1-Nonprofessional	69.73	8.52	50.66	84.03
	IFOV2	67.43	10.99	49.19	91.36
	IFOV2-Male	68.47	11.25	49.84	91.36
	IFOV2-Female	66.24	10.83	49.19	91.00
	IFOV2-Professional	66.10	10.02	49.84	86.72
	IFOV2-Nonprofessional	68.82	11.98	49.19	91.36
	IFOV3	64.30	9.76	39.91	84.75
	IFOV3-Male	65.57	11.17	39.91	84.75
	IFOV3-Female	62.85	7.87	44.20	74.99
	IFOV3-Professional	63.26	10.25	39.91	84.75
	IFOV3-Nonprofessional	65.39	9.33	45.67	84.71
Gender	Male	67.82	10.04	39.91	91.36
	Female	64.58	8.98	44.20	91.00
Professional status	Professional	64.71	9.03	39.91	86.72
	Nonprofessional	67.98	10.08	45.67	91.36
Total		66.29	9.54	44.21	88.66

Note: S.D. = standard deviation.

Table 2: Descriptive statistical results for COR

Factor	Classification	Outcome				
		Collision		Non-collision		
		Count	N%	Count	N%	Total
Gender	Male	27	37.50%	45	62.50%	72
	Female	19	30.16%	44	69.84%	63
Professional status	Professional	21	30.43%	48	69.57%	69
	Nonprofessional	25	37.88%	41	62.12%	66
IFOV levels	**IFOV1**	23	51.11%	22	48.89%	45
	IFOV1-Male	13	54.17%	11	45.83%	24
	IFOV1-Female	10	47.62%	11	52.38%	21
	IFOV1-Professional	9	39.13%	14	60.87%	23
	IFOV1-Nonprofessional	14	63.64%	8	36.36%	22
	IFOV2	14	31.11%	31	68.89%	45
	IFOV2-Male	8	33.33%	16	66.67%	24
	IFOV2-Female	6	28.57%	15	71.43%	21
	IFOV2-Professional	7	30.43%	16	69.57%	23
	IFOV2-Nonprofessional	7	31.82%	15	68.18%	22
	IFOV3	9	20.00%	36	80.00%	45
	IFOV3-Male	6	25.00%	18	75.00%	24
	IFOV3-Female	3	14.29%	18	85.71%	21
	IFOV3-Professional	5	21.74%	18	78.26%	23
	IFOV3-Nonprofessional	4	18.18%	18	81.82%	22
Total		46	34.07%	89	65.93%	135

Table 3: Parameter estimates of logistic regression models for COR

Mode	Variable	Level	B	S.E.	Wald	df	Sig.	Exp(B)
COR	Gender	Male vs. Female	0.349	0.383	0.832	1	0.362	1.418
	Professional status	Professional vs. Nonprofessional	-0.353	0.380	0.860	1	0.354	0.703
	IFOV levels	IFOV1			9.584	2	0.008	
		IFOV2	-0.852	0.442	3.707	1	0.054	0.427
		IFOV3	-1.450	0.481	9.085	1	0.003	0.235
	Constant		0.039	0.413	0.009	1	0.925	1.040

Table 4: Descriptive statistical results and chi-square tests for CAMs

Factor	Classification	CAMs						Chi-square Test
		DCA		ACA		NCA		
		Count	N %	Count	N %	Count	N %	*p*-value
Gender	Male	50	69.44%	6	8.33%	16	22.22%	0.369
	Female	49	77.78%	4	6.35%	10	15.87%	
Professional status	Professional	51	73.91%	6	8.70%	12	17.39%	0.362
	Nonprofessional	48	72.73%	4	6.06%	14	21.21%	
IFOV levels	**IFOV1**	24	53.33%	5	11.11%	16	35.56%	0.007**
	IFOV1-Male	12	50.00%	2	8.33%	10	41.67%	
	IFOV1-Female	12	57.14%	3	14.29%	6	28.57%	
	IFOV1-Professional	14	60.87%	3	13.04%	6	26.09%	
	IFOV1-Nonprofessional	10	45.45%	2	9.09%	10	45.45%	
	IFOV2	37	82.22%	1	2.22%	7	15.56%	
	IFOV2-Male	19	79.17%	1	4.17%	4	16.67%	
	IFOV2-Female	18	85.71%	0	0.00%	3	14.29%	
	IFOV2-Professional	19	82.61%	0	0.00%	4	17.39%	
	IFOV2-Nonprofessional	18	81.82%	1	4.55%	3	13.64%	
	IFOV3	38	84.44%	4	8.89%	3	6.67%	
	IFOV3-Male	19	79.17%	3	12.50%	2	8.33%	
	IFOV3-Female	19	90.48%	1	4.76%	1	4.76%	
	IFOV3-Professional	18	78.26%	3	13.04%	2	8.70%	
	IFOV3-Nonprofessional	20	90.91%	1	4.55%	1	4.55%	
Collision occurrence ratio	Non-collision	77	77.78%	3	30.00%	9	34.62%	
	Collision	22	22.22%	7	70.00%	17	65.38%	
	Total	99	73.33%	10	7.41%	26	19.26%	

Note: **Significant at 0.01 level. *Significant at 0.05 level.

Table 5: Descriptive statistical results and Type Ⅲ tests of fixed effects for BTI

Source	Numerator df	Denominator df	F		Mean (M)	S.D.	Min	Max
Gender	1	80.29	0.93	Male	2.45	1.35	0.43	4.42
				Female	2.24	1.29	0.42	4.40
Professional status	1	79.64	5.60*	Professional	2.50	1.36	0.43	4.40
				Nonprofessional	2.18	1.27	0.42	4.42
IFOV levels	2	54.67	21.47**	**IFOV1**	1.33	1.04	0.42	4.37
				IFOV1-Male	1.54	1.39	0.50	4.37
				IFOV1-Female	1.13	0.56	0.42	2.37
				IFOV1-Professional	1.67	1.20	0.48	4.37
				IFOV1-Nonprofessional	0.79	0.35	0.42	1.27
				IFOV2	2.31	1.18	0.43	4.25
				IFOV2-Male	2.32	1.16	0.43	4.25
				IFOV2-Female	2.31	1.24	0.55	4.18
				IFOV2-Professional	2.60	1.29	0.43	4.25
				IFOV2-Nonprofessional	2.01	1.00	0.57	4.02
				IFOV3	3.05	1.19	0.57	4.42
				IFOV3-Male	3.18	1.16	0.57	4.42
				IFOV3-Female	2.92	1.23	0.78	4.40
				IFOV3-Professional	3.12	1.27	0.78	4.40
				IFOV3-Nonprofessional	2.99	1.14	0.57	4.42
				Total	2.35	1.32	0.42	4.42
IFOV levels * Gender	2	54.96	0.09					
IFOV levels * Professional status	2	54.58	0.79					
Gender * Professional status	1	78.11	2.57					

Note: S.D. = standard deviation. **Significant at 0.01 level. *Significant at 0.05 level.

Table 6: Analysis of variance for DNS

Source	df			Speed 95m	Speed 90m	Speed 85m	Speed 80m	Speed 75m	Speed 70m	Speed 65m	Speed 60m	Speed 55m	Speed 50m
Gender	1		F-ratio	3.78	3.18	2.59	2.01	1.48	1.06	0.65	0.32	0.14	0.04
Profession	1		F-ratio	3.89	3.97*	3.91*	3.80	3.87	4.12*	4.57*	5.05**	5.70*	6.29*
IFOV	2		F-ratio	1.54	1.55	1.53	1.60	1.79	2.10	2.57	3.42*	4.78**	6.44**
Post Hoc Tests (LSD)		IFOV1-IFOV2	Mean Difference	-0.24	-0.05	0.27	0.69	1.20	1.75	2.21	2.66	3.22	3.86
		IFOV2-IFOV3	Mean Difference	3.13	3.11	3.01	2.94	2.96	3.09	3.51	4.30	5.34	6.39*
		IFOV1-IFOV3	Mean Difference	2.89	3.05	3.28	3.64	4.16	4.84*	5.71*	6.97*	8.56**	10.25**

Source	df			Speed 45m	Speed 40m	Speed 35m	Speed 30m	Speed 25m	Speed 20m	Speed 15m	Speed 10m	Speed 5m	Speed 0m
Gender	1		F-ratio	0.01	0.01	0.01	0.0	0.00	0.01	0.13	0.74	2.19	4.49*
Profession	1		F-ratio	6.77*	6.69*	6.11*	5.18*	4.49*	3.78	2.56	2.14	1.93	1.21
IFOV	2		F-ratio	8.57**	11.24**	13.22**	13.86**	13.67**	13.53**	13.15**	11.61**	8.36**	4.71*
Post Hoc Tests (LSD)		IFOV1-IFOV2	Mean Difference	4.78	5.80	6.76*	7.79*	9.11**	10.74**	12.06**	11.96**	10.29**	7.29
		IFOV2-IFOV3	Mean Difference	7.45*	8.89**	9.92**	9.84**	9.05*	8.01*	7.08	6.30	5.36	4.55
		IFOV1-IFOV3	Mean Difference	12.22**	14.69**	16.68**	17.62**	18.16**	18.75**	19.14**	18.26**	15.65**	11.84**

Note: **Significant at 0.01 level. *Significant at 0.05 level.

Table 7: Descriptive statistical results and Type Ⅲ tests of fixed effects for DEC

Source	Numerator df	Denominator df	F		Mean (M)	S.D.	Min	Max
Gender	1	29.34	5.34*	Male	-2.90	1.80	-7.53	-0.13
				Female	-3.87	2.03	-7.50	-0.14
Professional status	1	29.34	1.85	Professional	-3.22	1.90	-7.53	-0.14
				Nonprofessional	-3.56	2.05	-7.50	-0.13
IFOV levels	2	38.81	6.18**	**IFOV1**	-4.49	2.28	-7.53	-1.10
				IFOV1-Male	-3.61	2.50	-7.53	-1.10
				IFOV1-Female	-5.37	1.70	-7.50	-2.49
				IFOV1-Professional	-4.02	2.25	-7.53	-1.10
				IFOV1-Nonprofessional	-5.15	2.26	-7.50	-1.39
				IFOV2	-3.29	1.95	-7.04	-0.13
				IFOV2-Male	-2.88	1.68	-7.04	-0.13
				IFOV2-Female	-3.72	2.15	-6.91	-0.14
				IFOV2-Professional	-3.28	1.95	-6.77	-0.14
				IFOV2-Nonprofessional	-3.30	2.00	-7.04	-0.13
				IFOV3	-2.77	1.49	-7.17	-1.04
				IFOV3-Male	-2.47	1.30	-5.80	-1.11
				IFOV3-Female	-3.06	1.64	-7.17	-1.04
				IFOV3-Professional	-2.53	1.31	-5.77	-1.12
				IFOV3-Nonprofessional	-2.99	1.64	-7.17	-1.04
				Total	-3.44	1.93	-7.40	-0.40
IFOV levels * Gender	2	38.81	0.46					
IFOV levels * Professional status	2	38.81	0.34					
Gender * Professional status	1	29.34	0.05					

Note: S.D. = standard deviation. **Significant at 0.01 level. *Significant at 0.05 level.

Table 8: Correlation analyses for variables

Correlations					
	IFOV levels	Entry speed	Brake time to Intersection	Deceleration rate	Crash rate
IFOV levels	1	-0.176	0.500**	-0.330**	-0.284**
Entry speed	-0.176	1	-0.283**	0.116	0.320**
Brake time to intersection	0.500**	-0.283**	1	-0.529**	-0.594**
Deceleration rate	-0.330**	0.116	-0.529**	1	-0.06
Crash rate	-0.284**	0.320**	-0.594**	-0.06	1

Note: **Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).