Traffic & Transportation

Exploring Driver Trajectory Preferences for Unprotected Left Turns and the Impact on Traffic Safety

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Original Scientific Paper
Submitted: 25 Oct 2024
Accepted: 20 Feb 2025

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Publisher:
Faculty of Transport and Traffic Sciences, University of Zagreb

ABSTRACT

The behaviour of drivers making left turns is complex, significantly affecting the safety of intersection operations. Some drivers disregard the right-of-way rules when making left turns, leading to contention with vehicles going straight, causing chaotic trajectories and widening the potential conflict area with straight-moving vehicles. This study analyses the left turn trajectory preference of drivers under different intersection conditions and compares the effects of various intervention measures in enhancing intersection safety. Twenty-seven scenarios were created with different sign and marking designs and traffic conditions using a driving simulator. Forty-four participants were recruited to gather driving data, such as speed and position, to extract key evaluation indicators representing drivers' left turn behaviour. In addition, a one-way analysis of variance is conducted to explore the trajectory perspective on horizontal curves, driver gap acceptance time and post-encroachment time during left turn. The results revealed that drivers' trajectories leaned more towards the left side when making left turns under crossing decisions. Whereas under yielding decisions, drivers' trajectories stayed closer to the right side. Additionally, the absolute deviation of trajectories under yielding decisions was greater than those under crossing decisions. The findings confirm that the left-turn guidelines can influence left-turn driving behaviour to enhance safety.

KEYWORDS

driving behaviour; trajectory preference; unprotected left-turn; driving simulator; intersections.

1. INTRODUCTION

Improving road safety is undoubtedly one of the biggest challenges today. The numbers of road crashes, injuries and fatalities are staggering worldwide. The Global status report on road safety 2023 shows that the number of annual road traffic deaths is 1.19 million [1]. The data reveal that one-fifth of traffic crashes and one-sixth of fatal traffic crashes occur at intersections, making intersections hotspots for frequent traffic crashes [2, 3]. Hence, studying driver behaviour at intersections holds significant importance.

Intersections act as pivotal nodes for traffic flow, presenting a more complex traffic environment that demands high reaction capabilities and driving skills from drivers. Numerous factors contribute to high crash rates at intersections, with left-turn conflicts being one of the primary causes [4-6]. Especially in unprotected left-turn conditions, left-turn drivers are required to yield to oncoming traffic and crossing pedestrians. When sufficient gaps are available, the left turn can be executed, potentially reducing running delays [7, 8]. Yet, in certain circumstances, this might have adverse safety implications as drivers need to assess and act based on gaps in oncoming traffic flow [9, 10]. Consequently, many crashes involving left-turning vehicles can be attributed to improper gap selection [11]. This underscores the need for a better understanding of driver left turn crossing behaviour to provide measures aimed at enhancing left turn safety for drivers.

Drivers' decisions are often influenced by various factors such as driver personality traits (i.e. aggressive, conservative) and environmental conditions. Different factors lead to varied preferences among drivers. Previously, the calculation of gaps was based on fixed trajectories, without considering the discrete characteristics. It is necessary to study the safety of drivers' left-turn behaviour under different conditions considering trajectory preferences.

1.1 Related works

Intersections constitute vital components of road networks, holding critical functionality in both urban and rural environments. Despite their functional value, intersections pose concentrated risks to road users due to the relatively complex tasks involved in safe driving. Conflicts between left-turn vehicles and opposing through movement can potentially cause accidents. Therefore, understanding how different factors influence the behaviour of left-turn drivers and their yielding to opposing through movement becomes crucial.

Numerous studies have been developed on contributing factors to left turn behaviour and crashes involving left turns. Factors influencing left-turn driving decisions encompass various elements, including network topography, traffic conditions and driver characteristics [12-14]. Some studies have utilised additional data sources to conduct more specific examinations into crash causes involving drivers. In such investigations, inappropriate gap selection and high task complexity have emerged as leading factors contributing to most crashes [15].

Gap acceptance time can significantly impact the driver's left turn behaviour. Most drivers tend to reject gaps between vehicles lasting less than or equal to 3 seconds, yet nearly all drivers accept gaps of 12 seconds or more [16]. However, recent studies indicate a significant influence of human factors on drivers' gap acceptance decision-making: driver errors (lack of concentration, pressure from risky behaviour) and personal objectives and attitudes (speeding, personality traits, reaching destinations within set timeframes) [17]. In a study by Paschalidis, Choudhury [17], time pressure was introduced to explore its impact on drivers' gap acceptance behaviour at intersections using driving simulators. Participants deliberately experienced pressure induced by time constraints, leading to the development of a discrete choice model linking drivers' acceptance-rejection decisions to demographics, traffic conditions and stress levels. The model results revealed a substantial increase in the likelihood of accepting gaps with increased stress levels. Other studies, such as Li, Oviedo-Trespalacios [18] explored the impact of using mobile phones on gap acceptance at intersections. They proposed that intersection type and size significantly influence decision-making and completion time for gap acceptance at intersections. Additionally, Pawar and Velaga [19] used crash probability assessment to analyse the influence of time pressure on driving decisions and safety under various driving conditions.

Crash analysis stands as the most direct and commonly used method for evaluating traffic safety. There are two commonly used methods to analyse left turn safety using either historical crash data or safety indicators. However, historical crash data have at least two limitations. Firstly, the relative rarity and randomness of crashes make them challenging to study without ample historical data. Secondly, not all crashes are publicly reported, with the degree of underreporting depending on the severity of the crash and the types of road users involved. Thus, alternative safety indicators serve as alternative or complementary methods for identifying safety issues [20].

Four primary types of data are used to analyse driver behaviour and its impact on traffic: driver behaviour questionnaires, driving simulators, road experiments and naturalistic driving studies [21-23]. Driving simulators are a low-cost method for analysing driver behaviour, creating various traffic scenarios and recording detailed driver actions and operations. Compared to similar real-world or on-road driving studies, advanced driving simulators have several advantages, including experimental control, efficiency, cost-effectiveness, safety and ease of data collection. Driving simulator technology has been widely employed in research related to traffic safety, vehicle design and driving impairments, examining individual driver differences, vehicle technology, road design effects and the effectiveness of safety interventions [24].

Driving simulators have been utilised in studies related to individual differences and driver states, exploring these differences in specific environments to gain deeper insights into situations that are challenging to measure in naturalistic driving studies [25]. Hussain, Alhajyaseen [26] evaluate the subjective perception of speed in the simulator through the posterior questionnaire and the driver's subjective evaluation. The results support the subjective validity of the simulation results of the driving simulator. With its reproducible scenario for repeated experiments and ability to test high-danger driving scenarios (such as the small gap scenarios), the driving simulator offers high safety, economy and controllability for collecting driving behaviour data, which makes it a widely used tool in traffic safety study [27].

The calculation of crossing gaps at intersections and other traffic safety indicators is based on given trajectories and conflict points in most of the existing studies. However, vehicle trajectories have an intrinsic dispersion nature, which leads to discrepancies from the actual values in the calculation of gaps and other safety indicators. In this study, we aim to analyse the left turn trajectory preference of drivers considering the dispersion of vehicle trajectories under a weakened lane environment. Driver preference during an unprotected left turn is investigated by considering different crossing angles, gap sizes and intervention measures using a driving simulator.

1.2 Objective and contribution

The existing studies on driving behaviour highlight the close relationship between driver characteristics, driving environments and traffic safety. However, most findings relied on the fixed trajectories, without considering the discrete characteristics, lacking in-depth discussion regarding drivers' trajectory preferences. Therefore, this paper delves deeper into driver trajectory preferences for unprotected left turns and their impact on traffic safety. It considers the influence of crossing angle, gap size and intervention measures. The aim is to better understand driver behaviour from a trajectory perspective on horizontal curves, analyse trajectories based on different working conditions, explore driver gap acceptance under different conditions and quantitatively analyse left-turn driving behaviour. The specific research questions are as follows.

1) Analysing driver decisions (crossing/yielding) under different crossing angles, gap sizes and intervention measures.
2) Studying the correlation between trajectories and driver decisions, as well as investigating trajectories and operational safety.
3) Providing insights into the effect of setting up stop signs and left-turn guidelines, assessing their influence on driver trajectories and their potential positive impact on intersection safety.

The primary contribution of this research lies in adding the consideration of the behavioural preferences of trajectories into the analysis of the driver decisions for unprotected left turns and their impacts on safety. Additionally, two measures are compared to assess their impact on drivers' preference choices and their effectiveness in enhancing safety.

The remainder of the paper is organised as follows. Section 2 provides a summary of the experimental design, introducing the experimental objectives and the design of experimental scenarios. Section 3 presents a statistical analysis of the collected experimental data. Section 4 presents the relationship between trajectory preference and different driver behaviours, as well as the impact on traffic safety with and without intervention measures. Section 5 summarises the findings and conclusions of the study.

2. DRIVING SIMULATOR EXPERIMENTS

This study uses a driving simulator experiment and assesses trajectory-related data to evaluate the impact of intersection angle, gap size, road markings and driver personalities on left turn preferences.

2.1 Driving simulator

The driving simulation experiment, depicted in *Figure 1*, utilised the three-degree-of-freedom driving simulator from the Traffic Engineering Laboratory of the University of Shanghai for Science and Technology. The simulator comprises a driving cabin, a three-degree-of-freedom motion simulation platform from Canada, traffic scene simulation software named the Silab from Germany's WIVW, a 180-degree panoramic projection, rear-view projections, IT control devices and display monitoring equipment. The driver's feedback is controlled by force feedback steering wheels, brakes and throttle pedals, providing quick response and realistic road feedback, capable of simulating both large and small vehicles. Three projectors ensure a 180-degree wide-screen image as the foreground simulation display for the entire driving simulator system, with a visual scene resolution of 1920*1200 pixels. Environmental sounds (such as vehicle engines and other vehicles within the scene) are emitted within the vehicle to enhance the experiment's realism. Throughout the simulation, the system records various dynamic parameters (such as vehicle speed, acceleration, etc.) that describe the driver's driving behaviour.

Figure 1 – Three degrees of freedom driving simulator

2.2 Driving scenarios

Three factors are considered in the driving scenario design: crossing angle, gap size and intervention measure, as shown in *Table 1*. For crossing angle, the experiment involves intersections with three levels, set at 60°, 90° and 120°, as shown in *Figure 2*. For gap size, the experiment involves three levels, set at 2 s, 4 s and 6 s. For intervention measures, two measures to improve intersection safety were considered in the experiment: left-turn guideline and stop sign, in addition to the no-measure case. Therefore, in total $3 \times 3 \times 3 = 27$ left turn driving scenarios are set in the experiment.

We consider two intervention measures: left-turn guideline and stop sign. (1) Installing a left-turn guideline within the intersection helps direct left-turning vehicles. This guiding line can offer clear directional guidance to facilitate appropriate turning actions for drivers. An illustration is provided in *Figure 3(a)*. (2) Placing a stop sign before the stop line to guide drivers to stop at that location. This measure aims to provide drivers with more time and space to observe the intersection, potentially enhancing the safety of their decision-making process. An example is depicted in *Figure 3(b)*.

Table 1 – Description of experimental variables

Level	Intersection angle	Gap	Intervention measure
1	60°	2s	None
2	90°	4s	Stop sign
3	120°	6s	Left-turn guideline

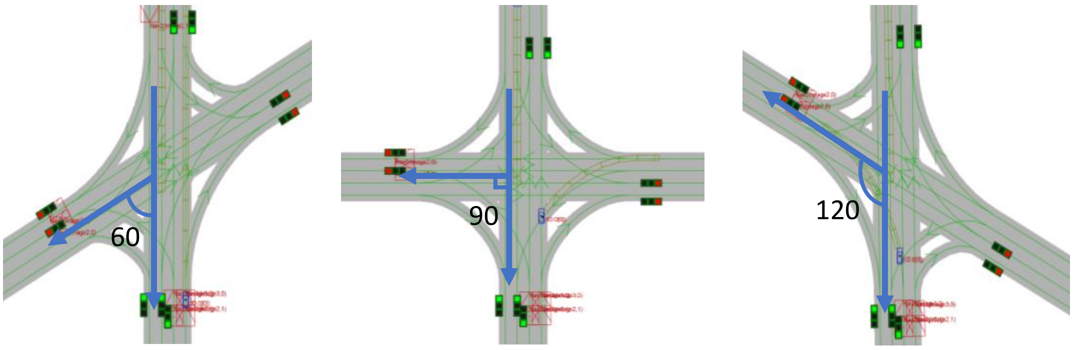
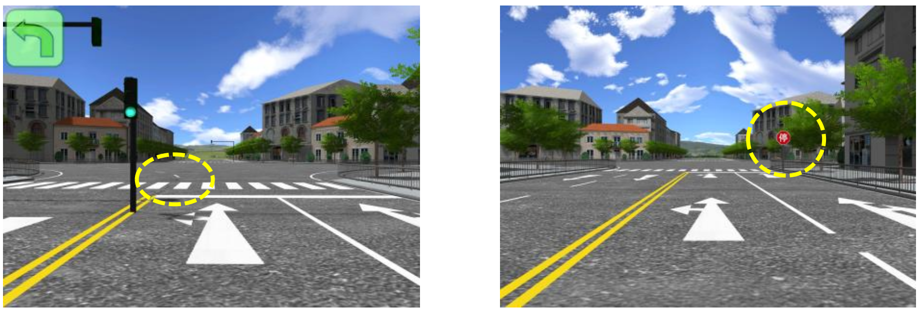


Figure 2 – Different intersection angles



(a) *(b)*

Figure 3 – Intervention measures within intersection in simulation scenario: a) left-turn guideline; b) stop sign

2.3 Experimental design

The entire road scenario is created using SILABAEdit, and specific parameters and navigation are configured using the backend editing language. The road is designed as a two-way, four-lane road with lane widths of 3.5 meters. To ensure the experiment's randomness, the tested 27 intersections (left turn), connecting sections and other intersections (through movement) are arranged randomly to form an approximately 20-kilometre urban road. This randomness helps prevent the results from being influenced by the same sequence of factors. *Figure 4* illustrates a sequence example of experimental intersections in the simulated scenario. The road scene, including the traffic signs and markings, is designed according to the national standards of China.

During the experiment, participants follow audio and image navigation to perform left or right turns at intersections. When the driver approaches an intersection requiring a left turn, navigation information is provided at a distance of 100 meters from the intersection. At a distance of 20 meters from the stop line, the navigation provides an audio prompt once more. One challenge in designing this experiment is enabling drivers to accept a gap and complete a left turn as they would in the real world. For intersections with oncoming traffic, the oncoming vehicles appear at a distance of 70 meters from the intersection under different gap conditions, ensuring that the appearance of oncoming vehicles does not cause panic for the driver, allowing them to make appropriate decisions.

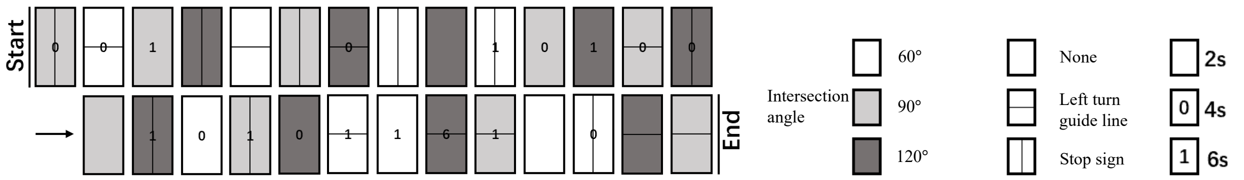


Figure 4 – Sequence of experimental intersections in the simulated scenario

2.4 Participants

A total of 44 participants (18 females and 26 males) comprised the initial sample. All were between 20 and 60 years old. All drivers had normal vision (correctable to normal with glasses or lenses), no hearing impairments or other illnesses, and held a valid Chinese driver's licence for at least 2 years. None of these drivers had previous experience with a driving simulator.

2.5 Experimental procedure

Before participating, each participant had to sign a consent form outlining the purpose of the study, potential risks and their rights as participants. They were informed that they could stop the experiment at any time and press the red emergency brake button in the simulated vehicle in case of an urgent issue.

Each driver performed the following tasks: driving once in a pre-prepared pre-driving scenario. The reason for not using the experimental scenario was to prevent participants from remembering the scene. This pre-driving session lasted for five minutes. The experimental protocol provided an initial explanation of the training scenario to help participants become familiar with the driving simulator tool. Subsequently, explanations were given about the visual and audio navigation systems to familiarise participants with the systems and prompts within the simulated scenarios. Before the test began, participants were informed only about the upcoming left or right turn prompts near the intersection, without any further instructions, to avoid influencing the drivers' choices and behaviour. Only drivers who pass the pre-driving scenario without any mistake could participate in the driving experiment.

Each experiment began with the participant at an initial distance of 200 m from the first intersection scene. Data were collected in the background at a sampling frequency of 20 Hz, directly recording driving parameters: time, main vehicle speed, real-time position of the main vehicle, real-time position of oncoming vehicles and other auxiliary parameters. The entire experiment process lasted approximately 40 minutes.

2.6 Data collection

The focus of this study lies in assessing drivers' preferences and safety evaluations based on their operational choices. Therefore, we analyse post-event data to understand the drivers' decision-making process. Dependent variables were generated to capture environmental and individual characteristics in drivers' operational decisions. Thus, three dependent variables were derived: (1) crossing/yielding decision, (2) trajectory deviation and (3) PET index. Throughout the experiment, we organised all data according to different independent variables, which include: (1) intersection angles, (2) TTA (time-to-arrival), (3) different measures and (4) driver personal traits. Subsequently, we provide further explanations on obtaining data for these dependent variables.

Crossing/Yielding

To preliminarily assess drivers' driving preferences, the driver's behaviour of crossing or yielding at intersections was selected to represent their behavioural characteristics. This metric determines the subject vehicle's crossing or yielding at the conflict point concerning the oncoming vehicle, which is more accurate than relying solely on braking data. Because drivers with different characteristics have different driving habits, some may yield with partial braking, while others might yield with complete braking, and some may cross with partial braking. Therefore, braking data alone cannot fully represent the yielding behaviour of drivers. Hence, in this study, the crossing/yielding behaviour is defined based on the sequence of the conflict point's timing as follows.

Crossing: The driver crosses the intersection before the oncoming vehicle arrives, i.e. the subject vehicle passes the point where the trajectories of the two vehicles intersect before the oncoming vehicle.

Yielding: The driver yields by completing the left turn after the oncoming vehicle passes, i.e. the oncoming vehicle passes the point where the trajectories of the two vehicles intersect before the subject vehicle.

Trajectory deviation

Trajectory deviation reflects the spatial dispersion of a driver's path while navigating through an intersection. Essentially, it compares the actual driving trajectory with a standard trajectory, measuring the difference in distance between them. Establishing an objective comparison standard is essential before determining any deviation, specifically a reference point for calculating the trajectory deviation when a vehicle passes through an intersection as shown in *Figure 5*.

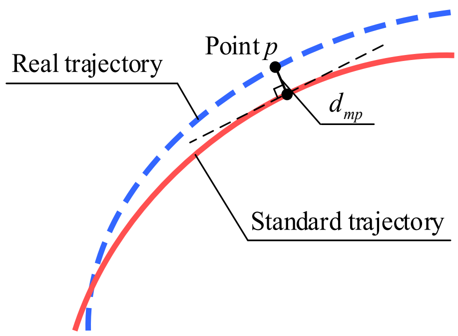


Figure 5 – Distance between the trajectory point and the standard trajectory

Due to the influence of intersection geometry and driver characteristics, different drivers exhibit varying trajectories while making left turns at intersections. To quantify drivers' driving characteristics, the concept of trajectory deviation is proposed to describe the degree to which each driver's trajectory deviates from the standard trajectory. In this driving simulation experiment, the trajectory of the oncoming straight-going vehicle is visualised from the entrance lane through the intersection to the exit lane. In left-turn driving, the subject vehicle only has a single left-turn entrance lane, while there are two exit lanes for left turns. Therefore, referring to Zhao et al. [28-30], a trajectory model describing vehicles passing through intersections based on optimal control theory is adopted. This model can plan the path of manually driven vehicles. Leveraging this model and actual driving data, the parameters are fitted aiming to minimise the standard deviation between the actual and standard trajectories, thus obtaining the standard trajectory for left-turn driving.

For the vehicle trajectory in this study, the driving path is represented as a two-dimensional curve. Considering the standard trajectory as the baseline, deviations to the left are denoted as "-" and deviations to the right as "+". The final formula represents the trajectory deviation indicator. The trajectory deviation is the average of the distances between point i on the actual trajectory and the nearest point on the standard trajectory, as shown in *Eq. (1)*. This deviation is calculated as the sum of these distances along the actual trajectory, where each point's deviation is considered.

$$\sigma_m^p = \sqrt{\frac{1}{n}\sum_{i=1}^{n} {d_{mi}}^2} \tag{1}$$

where σ_m^P is the trajectory deviation of driver p at intersection m; d_{mi} is the distance between trajectory point i of driver p at intersection m and the standard trajectory of the corresponding lane; n is the number of trajectory points for driver p at intersection m.

Safety indicator PET

The safety indicator PET (post-encroachment time) is chosen as the evaluation indicator for the safety of left-turning driver behaviour to assess safety more accurately at intersections [31-33]. PET calculation does not require vehicle speed, direction, length, etc., making it useful for determining potential conflicts between intersecting vehicles' trajectories. PET measurement requires attention to two points: (1) the moment the first vehicle exits the conflict area and (2) the moment the second vehicle enters the conflict area, as shown in *Eq. (2)*

$$\text{PET} = |t_1 - t_2| \tag{2}$$

where t_1 indicates the moment when the left-turning vehicle reaches the conflict point; t_2 indicates the moment when the straight-going vehicle reaches the conflict point.

3. EXPERIMENT RESULTS

The experimental process involved collecting scene data and driver behaviour data. The descriptive analysis of each evaluation indicator is conducted to investigate the trajectory preference and safety performance under different scenarios. The relationships between the influencing factors and dependent variables (driver decisions, trajectory deviations and PET) are analysed.

3.1 Analysis of driver decisions

For driver decisions, according to the chi-square test results for several categorical variables presented in *Table 2*, with a significance threshold of 0.05, the variables "intersection angle" (F=6.673, p=0.036), "gap size" (F=189.405, p=0.000) and "intervention measures" (F=302.005, p=0.000) all exhibit significant correlations with drivers' left turn decisions.

Table 2 – Drivers' decision and chi-square test results

Independent variables	**Scenario**	**Drivers' decision**		**Chi-square test**	
		Crossing	Yielding	Value	p
Intersection angle	60°	61.1%	38.9%	6.673	0.036
	90°	60.6%	39.4%		
	120°	53.0%	47.0%		
Gap	2s	34.1%	65.9%	189.405	0.000
	4s	58.3%	41.7%		
	6s	82.3%	17.7%		
Intervention measure	Stop sign	23.2%	76.8%	302.005	0.000
	Left-turn guideline	73.0%	27.0%		
	None	78.5%	21.5%		

It is observed that as the intersection angle increases, fewer drivers choose to cross. As the turning radii increase, more drivers choose to yield. There are more instances of drivers choosing to cross than choosing to yield. Particularly, at a 120° intersection angle, there is a notable difference in decisions compared to the other two angles, with more drivers opting to yield in scenarios with larger intersection angles. The proportion of crossing decisions is highest at a 6 s gap (82.3%), significantly decreasing in scenarios with smaller gaps. Additionally, as the gap size increases, the proportion of yielding decisions gradually decreases.

Intervention measures have a significant impact on drivers' left turn decisions, especially the stop sign, which represents a traffic prohibition. It mandates vehicles to stop before the stop line, observe and confirm safety before proceeding. This sign notably guides drivers to yield to oncoming traffic. Compared to the baseline scenario without intervention, the stop sign undeniably reduces the number of drivers choosing to cross (23.2%). This also indicates that some drivers do not fully adhere to the stop sign rules. Moreover, in scenarios with a left-turn guideline, there is a slight reduction in the number of drivers choosing to cross (73.0% vs. 78.5%). This is because the left-turn guideline, to some extent, guides drivers to execute larger-radius turns. Hence, in such scenarios, some drivers opt to yield to oncoming traffic.

3.2 Analysis of trajectory deviation

T-tests show that there are significant differences in the mean and median trajectory deviations under different intersection angles, gap sizes and intervention measures. It can be seen in *Table 3*, that as the intersection angle increases, the mean trajectory deviation gradually decreases. This suggests that with larger intersection angles, drivers execute larger left turn radii, resulting in smoother trajectories. Similarly, as the crossing gap size increases, the left turn trajectory deviation reduces. This is because, in smaller gaps, more drivers choose to yield, waiting for oncoming traffic to pass before executing larger left turns upon entering the intersection. This behaviour leads to larger trajectory deviations. Under the stop sign intervention, the average trajectory deviation is 1.91 m, greater than the average deviation of 1.48 m in the baseline condition without intervention. Conversely, under the left-turn guideline intervention, the average trajectory deviation (1.11 m) is smaller than in the absence of intervention.

Table 3 – Descriptive analysis of trajectory deviation under different scenarios

Independent variables	Scenario	Mean	Median	Variance	SD	Min.	Max.
Intersection angle	60°	1.6451	1.2780	1.331	1.15364	0.23	7.96
	90°	1.4820	1.1724	1.034	1.01676	0.26	8.36
	120°	1.3702	1.1139	0.686	0.82803	0.22	7.85
Gap	2s	1.7647	1.3665	1.357	1.16471	0.23	8.36
	4s	1.4364	1.1239	0.979	0.98931	0.22	7.96
	6s	1.2954	1.1023	0.636	0.79760	0.27	4.93
Intervention measures	Stop sign	1.9075	1.6489	1.274	1.12861	0.22	5.95
	Left-turn guideline	1.1122	1.0302	0.429	0.65486	0.37	8.36
	None	1.4785	1.2237	1.069	1.03416	0.23	7.96

3.3 Analysis of PET

Table 4 shows the descriptive statistics of PET under various influencing factors. There are notable differences in the mean and median values under different gap sizes. At intersections with gap sizes of 2 s, 4 s and 6 s, the average PET values are 3.76 s, 4.21 s and 6.89 s, respectively. As the gap size increases, the PET value also increases.

Under the conditions of a stop sign, the average PET values are 4.76 s, lower than the baseline scenario without intervention (5.09 s). This is because the average value is derived from the calculation of PET for all drivers, and some drivers, under yielding decisions, immediately make the turn within the intersection after waiting for oncoming traffic to pass. This behaviour results in a lower average PET value compared to scenarios without intervention.

Table 4 – Descriptive analysis of PET under different scenarios

Independent variables	Scenario	Mean	Median	Variance	SD	Min.	Max.
Intersection angle	60°	4.9710	4.4502	4.179	2.04416	1.10	9.55
	90°	4.8758	4.5004	4.055	2.01381	1.25	9.80
	120°	5.0201	4.8500	2.785	1.66897	1.80	9.30
Gap	2s	3.7649	3.8252	1.583	1.25801	1.10	7.35
	4s	4.2110	4.1500	1.117	1.05702	1.45	8.60
	6s	6.8909	7.0500	2.598	1.61190	1.80	9.80
Intervention measures	Stop sign	4.7592	4.7000	1.524	1.23457	1.10	8.60
	Left-turn guideline	5.0135	4.5000	4.473	2.11483	1.25	9.25
	None	5.0941	4.5750	4.972	2.22987	1.35	9.80

4. TRAJECTORY PREFERENCE AND CROSSING SAFETY ANALYSIS

The relationship between trajectory preference and different driver behaviours, as well as the impact on traffic safety with and without intervention measures, are analysed. Different comparative statistical analysis methods were used to compare multiple sets of variables. Independent t-tests were used to evaluate mean differences in continuous variables between two study groups. Least significance difference (LSD) post hoc tests were utilised in Section 4.3 to assess the significance of ordered variable differences. Mean differences were examined through one-way analysis of variance (ANOVA) in Sections 4.3 and 4.4.

4.1 Analysis of trajectory without intervention measure

This section depicts the left turn trajectories under different scenarios. Utilising vehicle position data and considering the characteristics of left turns, trajectories were filtered out with abnormal distributions to obtain a sample of vehicle trajectories under normal conditions. Drivers' decisions were determined based on the time difference between the subject vehicle and the oncoming vehicle reaching the virtual conflict point. Using coordinates at the sampling frequency, the reference points were calibrated for the coordinate system. The trajectory points were plotted based on the vehicle's movement from reaching the stop line to completing the left turn into the downstream exit lane. The vehicle's position was recorded at a sampling frequency of 20 Hz. *Figure 6* illustrates the dispersion of left turn trajectories at different intersection angles and crossing gap scenarios.

In *Figure 6*, blue lines are used to present crossing behaviour, while yellow lines represent yielding behaviour. Regardless of the intersection angle, drivers who chose to cross generally veered toward the inner side of the turn. Some drivers even initiated sharp left turns immediately after crossing the stop line. Engaging in forceful left turns within smaller crossing gaps presents a significantly hazardous driving behaviour, greatly increasing the risk of traffic accidents.

The independent sample t-test was employed to validate whether there exists a statistically significant difference in trajectory deviation among drivers making different decisions. The dependent variable was the trajectory deviation value, while the independent variable was the driver's decision. The intersection data for the study were limited to scenarios without intervention measures, comprising a total of 1,188 samples. Descriptive statistics and results of the trajectory deviation under the crossing/yielding decision are presented in *Table 5*.

The t-test results indicate a significant effect of driver decision on left turn trajectory deviation ($F=143.824$, $p<0.001$); this corresponds to the case study results on the left-turning mopeds' behaviour at intersections [6]. Descriptively, drivers who cross ($M=1.148$, $SD=0.713$) tend to align their left turn trajectories more closely with the expected standard trajectory, showing smaller trajectory deviations. Conversely, drivers who yield ($M=1.975$, $SD=1.124$) exhibit larger deviations from the standard trajectory, with trajectories leaning towards the outside. Different driving habits and environments can influence varied left-turn behaviours among drivers. Drivers who choose to yield demonstrate greater trajectory deviations (average of 0.83 m) compared to those who cross. This suggests that drivers choosing to yield understand the higher risk involved in crossing before oncoming vehicles arrive. To avoid collision with oncoming vehicles, the yielding vehicles will make a detour outside the standard trajectory. Conversely, drivers who cross would use the expected route to make the left turn, leading to trajectories aligning more with the standard trajectory, consistent with real-world driving habits.

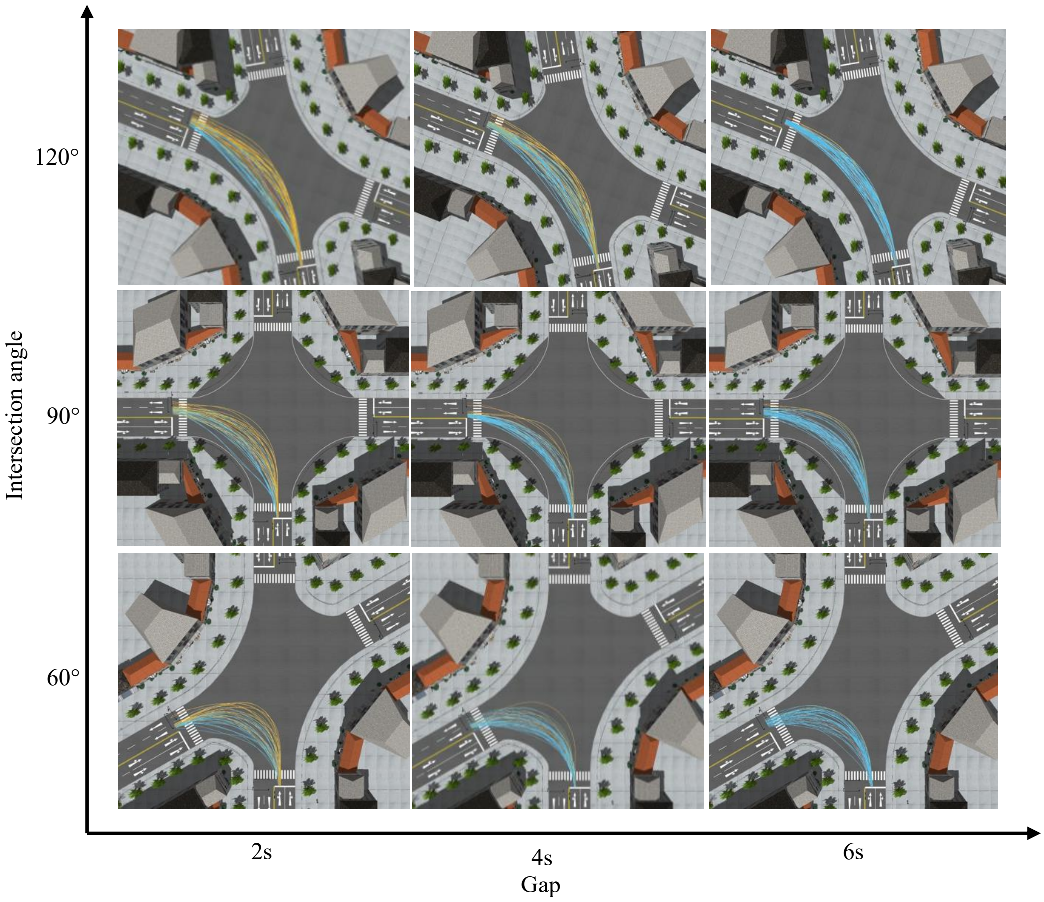


Figure 6 – Left turn trajectories at different intersection angles

Table 5 – Descriptive analysis of trajectory deviation under different driver behaviours

Decision group	Trajectory deviation (m)		
	Sample size	Mean	Standard deviation
Crossing	692	1.148	0.713
Yielding	496	1.975	1.124

Figure 7 consolidates scatter data of all drivers, depicting the average trajectory deviation while crossing intersections against the frequency of crossings. This scatter plot displays a strong pattern after data processing. The variation in average trajectory deviation mainly ranges between 1 m and 2 m. With the increase in crossing frequency, the distribution of data points becomes more concentrated, and the average trajectory deviation is also decreasing.

By conducting a Spearman rank correlation analysis of the drivers' crossing frequency and average trajectory deviation, a p-value of $p<0.001$ and a correlation coefficient of -0.643 are obtained. This outcome confirms a significant and negative relationship between crossing frequency and average trajectory deviation. It confirms the statistically significant correlation between crossing decisions and trajectories.

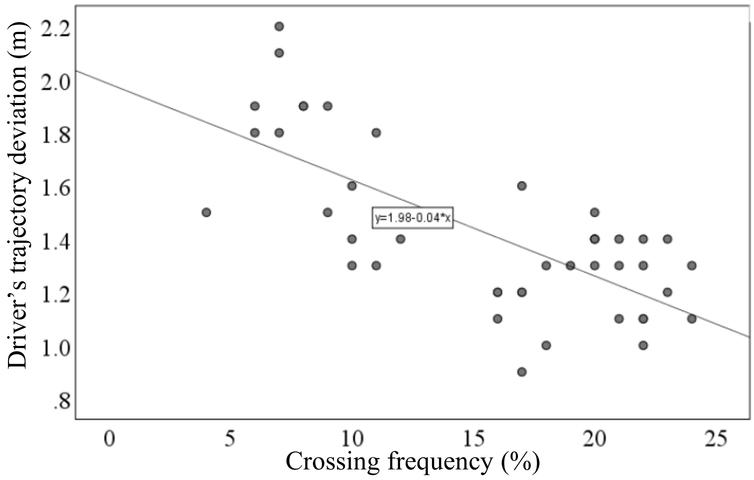


Figure 7 – Relationship between average trajectory deviation and crossing frequency

4.2 Analysis of safety without intervention measure

This section employs partial correlation analyses to examine the relationship between trajectory deviation and the safety metric PET at different gap sizes. Hence, the samples are grouped based on different gap sizes to explore the correlation between trajectory deviation and PET.

Table 6 indicates significant correlations between drivers' trajectory deviation and PET at gap sizes of 2 s and 6 s, while no apparent relationship exists at a 4 s gap. Additionally, from *Figure 8* it is evident that at a 2 s gap, the vertical distribution of scattered points is more concentrated, whereas at a 6 s gap, the vertical distribution is more dispersed. This can be explained by the fact that at smaller gaps, where crossing decisions are made, the gap is already relatively small. Hence, when drivers who decide to cross pass through the conflict point, the oncoming vehicle is already very close, resulting in minimal differences in PET values. On the other hand, at a 6 s gap, assuming that drivers have a preference for certain trajectory choices as a habit, even within a sufficiently large gap, some drivers might still exhibit more aggressive crossing behaviour, while others might adopt a more conservative approach. Consequently, this leads to a larger discrepancy in PET values.

Table 6 – Partial correlation analysis between trajectory deviation and PET

Item	Gap		
	2 s	4 s	6 s
Sample size	135	231	326
Correlation coefficient	0.387	-0.019	-0.294
Sig. (two tail)	0.000	0.714	0.000

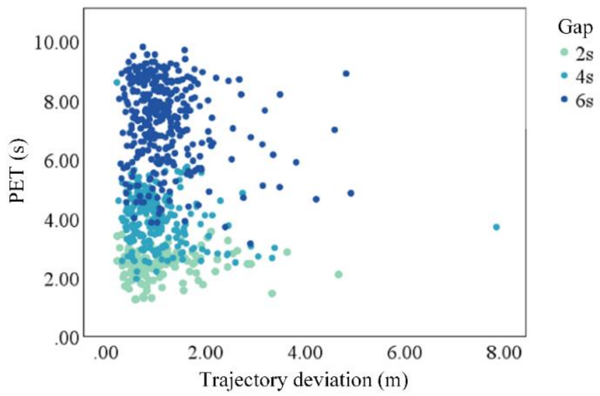


Figure 8 – The relationship between trajectory deviation and PET

The subsequent discussion aims to investigate whether drivers with different characteristics exhibit similar behavioural habits in different driving environments. Drivers are divided into two groups according to the turning behaviour at the 2 s gap, which is the crossing group and the yielding group, respectively. Earlier evidence has established a correlation between crossing decisions and trajectories, implying that there will likely be differences in trajectories between the two groups at smaller gaps due to more pronounced driving characteristic differences (decision behaviours) among drivers in smaller gaps.

To fairly compare whether the trajectory choices of these two groups represent habitual preferences, trajectory deviation at the larger gap is chosen for analysis. Thus, the driving trajectories of these two groups at a 6 s gap are compared. The results in *Table 7* indicate that among drivers opting to cross at the 2 s gap, the trajectory deviation for the crossing group at the 6 s gap is smaller (1.21 m). This suggests that most crossing drivers in this group maintain their driving characteristics even at larger gaps. Conversely, yielding drivers, even in larger gap situations, exhibit relatively larger trajectory deviations (1.36 m). Some drivers within the yielding group still opt to yield or execute larger turning angles for left turns at larger gaps. This implies that these drivers maintain conservative driving habits regardless of the environment. For driver characteristics, this represents a driving habit preference: drivers in the crossing group consistently make left turns based on expected behaviour regardless of gap size, while drivers in the yielding group exhibit yielding behaviour in various intersection environments.

Table 7 – Descriptive analysis of trajectory deviation at a 6 s gap

Decision group	**Trajectory deviation (m)**			
	Sample size	Mean at a 2 s gap	Mean at a 6 s gap	Standard deviation at a 6 s gap
Crossing at a 2 s gap	15	1.6483	1.2105	0.70287
Yielding at a 2 s gap	29	1.8825	1.3600	0.58166

4.3 Analysis of trajectory with intervention measure

The previous section analysed drivers' driving preferences and safety when left turning without intervention measures. It was established that driving safety is influenced by individual characteristics and driving environments, especially for aggressive drivers who choose to cross in smaller gaps, resulting in larger trajectory deviations and subsequently reduced safety during left turns. Therefore, this section explores the impact of various intervention measures on driver behaviour to determine if these interventions have compensatory effects. Separate one-way ANOVA analyses were conducted for drivers making the crossing and yielding decisions in *Table 8*. Prior to ANOVA, normality assessments were performed on all data, indicating normal distribution. ANOVA results indicated statistically significant differences ($p < 0.05$) in trajectory deviation among different interventions; this corresponds to the previous survey on path variations at intersections [29]. The intervention measures have a positive impact on the orderliness of left turn trajectories. The left-turn guideline can reduce the trajectory deviation by 11.5% and 52.7% for crossing and yielding scenarios, respectively. The stop sign can reduce the trajectory deviation by 15.2% for the yielding scenario. This suggests that left lane guidance exerts a constraining and guiding influence on driving trajectories across different driver characteristics, indicating a positive effect on orderly behaviour at intersections.

In *Table 9*, the effects of different intervention measures on trajectory deviation showed variability. Post hoc multiple comparisons were conducted to assess the significance of differences among various intervention measures. It is evident that all intervention measures significantly impact trajectory deviation for the crossing driver group. Specifically, the left-turn guideline leads to smaller trajectory deviations compared to the stop sign (a difference of 0.88 m). However, under the stop sign, the trajectory deviation is larger (by 0.71 m) compared to the condition without intervention. This might be attributed to the fact that crossing drivers tend not to adhere strictly to stop signs, failing to yield before the stop line and instead yielding after entering the intersection, leading to larger turning angles and, consequently, larger trajectory deviations. Similarly, for the yielding group, the left-turn guideline exhibits the most significant impact on trajectory deviation.

Analysing samples with different driving decisions and characteristics revealed varying degrees of impact from different intervention measures on trajectories. Among them, the left-turn guideline exhibited the most significant influence, capable of reducing the magnitude of trajectory deviation. It effectively guided and standardised drivers' left turn behaviour.

Table 8 – One-way ANOVA analysis of trajectory deviation

Intervention measure	Trajectory deviation	Crossing	Yielding
None	Mean	1.202	2.490
	Standard deviation	0.788	1.191
Left-turn guideline	Mean	1.063	1.177
	Standard deviation	0.575	0.445
Stop sign	Mean	1.234	2.111
	Standard deviation	0.811	1.133
F		3.973	52.78
p		0.020	0.000

Table 9 – Multiple comparison analysis of trajectory deviation (LSD test)

Decision group	(I)Intervention measures	(J)Intervention measures	(I-J)	SD	p	95% confidence interval	
						Lower limit	Upper limit
Crossing	Stop sign	Guideline	0.87540**	0.10026	0.000	0.6342	1.1166
		None	0.70803**	0.11212	0.000	0.4388	0.9773
	Guideline	Stop sign	-0.87540**	0.10026	0.000	-1.1166	-0.6342
		None	-0.16738	0.07266	0.065	-0.3419	0.0072
	None	Stop sign	-0.70803**	0.11212	0.000	-0.9773	-0.4388
		Guideline	0.16738	0.07266	0.065	-0.0072	0.3419
Yielding	Stop sign	Guideline	0.76670**	0.08058	0.000	0.5734	0.9600
		None	0.21702	0.10339	0.105	-0.0308	0.4648
	Guideline	Stop sign	-0.76670**	0.08058	0.000	-0.9600	-0.5734
		None	-0.54968**	0.08498	0.000	-0.7536	-0.3457
	None	Stop sign	-0.21702	0.10339	0.105	-0.4648	0.0308
		Guideline	0.54968**	0.08498	0.000	0.3457	0.7536

**Significant level 0.05; ** significant level 0.01*

4.4 Analysis of safety with intervention measure

In different driving conditions, drivers make distinct crossing decisions. When the gap is 2 s, 34.1% of drivers choose to cross. When the gap is 6 s, 82.3% of drivers opt to cross. This illustrates that even with a smaller gap, many drivers still choose to complete a left turn before oncoming vehicles arrive, which significantly compromises intersection safety. Analysing the effects of intervention measures on samples with different driving decisions helps assess the measures' role in enhancing left turn safety. The results in *Table 10* indicate that regardless of the crossing or yielding group, different intervention measures exhibit statistically significant differences in PET. Additionally, the impact of these measures differs between the two groups.

Further post-hoc comparative analysis was utilised to contrast the significant differences among various intervention measures. *Table 11* indicates that, for the crossing group, there is a statistically significant difference ($p < 0.05$) between the effects of yielding and the left-turn guideline. Under the left-turn guideline, the PET is significantly higher than yielding, indicating that even with a stop sign, some drivers still choose to cross. Stop signs represent traffic prohibition, requiring drivers to stop before the stop line, check for safety and proceed only if clear. However, drivers who opt to cross despite the prohibition sign inherently engage in risky behaviour, consequently resulting in lower safety levels compared to any other intersection condition.

The PET value for the crossing group under the stop sign is lower than without intervention measures. This might be because drivers consider yielding before making the left turn but eventually choose to cross, which somewhat reduces the hesitation time, thus lowering the PET value to some extent.

For the yielding group, intersection safety under the stop sign is significantly higher than both the left-turn guideline and the absence of intervention measures. However, with a left-turn guideline, the intersection's safety is lower than without intervention measures. This is because the left-turn guideline encourages drivers to follow a yielding trajectory closer to the standard path, resulting in smaller turning angles and an earlier arrival at conflict points, thereby reducing the PET value. Nevertheless, despite this, the yielding behaviour remains safe.

Table 10 – One-way ANOVA analysis of PET

Intervention measure	PET	Crossing	Yielding
Stop sign	Mean	4.7848	4.7515
	Standard deviation	1.51793	1.13785
Left-turn guideline	Mean	5.3384	4.1360
	Standard deviation	2.34185	0.83707
None	Mean	5.2765	4.4265
	Standard deviation	2.42134	1.08203
F		3.973	4.000
p		0.020	0.019

Table 11 – Multiple comparison analysis of PET

Decision group	(I)Intervention measures	(J)Intervention measures	(I-J)	SD	p	95% confidence interval	
						Lower limit	Upper limit
Crossing	Stop sign	Guideline	-0.55366*	0.20981	0.026	-1.0582	-0.0491
		None	-0.49177	0.20951	0.058	-0.9956	0.0120
	Guideline	Stop sign	0.55366*	0.20981	0.026	0.0491	1.0582
		None	0.06188	0.19450	0.984	-0.4038	0.5276
	None	Stop sign	0.49177	0.20951	0.058	-0.0120	0.9956
		Guideline	-0.06188	0.19450	0.984	-0.5276	0.4038
Yielding	Stop sign	Guideline	0.61548**	0.10396	0.000	0.3656	0.8654
		None	0.32503*	0.13429	0.050	0.0005	0.6495
	Guideline	Stop sign	-0.61548**	0.10396	0.000	-0.8654	-0.3656
		None	-0.29046	0.14256	0.124	-0.6346	0.0536
	None	Stop sign	-0.32503*	0.13429	0.050	-0.6495	-0.0005
		Guideline	0.29046	0.14256	0.124	-0.0536	0.6346

**Significant level 0.05; ** significant level 0.01*

The analysis indicates that different intervention measures have varying effects on left turn safety, as reflected in the different PET values. The installation of a left-turn guideline has a significant guiding and standardising effect on trajectory deviation. The installation of stop signs is intended for drivers to stop before the stop line, observe and confirm safety before making a left turn. However, it is observed that many drivers do not fully adhere to this traffic rule indicated by the stop sign. Instead, they choose to disregard the stop sign and proceed with the left turn or yield only after entering the intersection.

5. CONCLUSIONS

This study analyses the left turn trajectory preference of drivers under different intersection conditions and compares the effects of various intervention measures in enhancing intersection safety. It considers the influence of crossing angle, gap size and intervention measures on driving behaviour. A driving simulator is used to obtain data related to driving behaviour, allowing for a detailed analysis of vehicle trajectories and driving safety. The aim is to better understand driver behaviour from a trajectory perspective, explore driver gap acceptance under different conditions, and quantitatively analyse left-turn driving behaviour.

The experimental results indicate that different conditions have varying impacts on drivers' trajectory preferences, especially the significant effect of gap size on driving trajectory deviation, subsequently affecting driving safety. Drivers' trajectory choices vary under different crossing gap sizes, influenced by the driving environment. The main findings are as follows.

1) There are substantial differences in trajectory selection between crossing and yielding drivers. Drivers who make the crossing decision show smaller trajectory deviations (mean = 1.148, SD = 0.713) from the standard trajectory. Conversely, drivers who yield exhibit larger deviations (mean = 1.975, SD = 1.124). Drivers who choose to yield tend to make a long detour to avoid conflict while maintaining their moving speed.
2) The intervention measures have a positive impact on the orderliness of left turn trajectories. The left-turn guideline can reduce the trajectory deviation by 11.5% and 52.7% for crossing and yielding scenarios, respectively. The stop sign can reduce the trajectory deviation by 15.2% for the yielding scenario.
3) The left-turn guideline and stop sign have a positive impact on traffic safety. For the crossing driver group, the left-turn guideline leads to a significantly larger PET compared to the stop sign (by 0.55 s) and the condition without intervention (by 0.06 s). For the yielding driver group, the PET under the stop sign is significantly larger compared to the left-turn guideline (by 0.62 s) and the condition without intervention (by 0.29 s).

While our study demonstrated diverse left turn preferences among different drivers, there are still some limitations of this study. Further studies are required to expand and validate the findings in this study. In future studies, incorporating additional influencing factors and intervention measures is much needed to enhance the safety of intersections. Also, future advanced driving assistance system solutions will be studied, which might potentially enhance efficiency by adapting to individual driver traits without compromising acceptability.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China under Grant 52372304.

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