

## Research Article

# Analysis of Drivers' Eye-Movement Characteristics When Driving around Curves

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To investigate drivers' visual strategies and the distribution of fixation points, much work had been done and salient conclusions had been drawn. However, there is still no consensus on what the gaze target is and what functional significance the point might have. To improve theories on this subject, research was done to investigate drivers' visual characteristics. On-road experiment was carried out, and drivers' eye-movement and vehicle driving parameters were registered when driving around left- and right-hand curves. The results showed that drivers' gaze direction fluctuates around the reference axis, and the fixation points are distributed in the region centered on the horizontal gaze position rather than a particular point that has geographical meanings. With the consideration of the traffic rules in China, we suggest here that there is no particular point on which drivers concentrate. Any point or position that could indicate the bend's curvature could be the so-called target point. Drivers just want to operate their vehicle so as to pass through bends safely in a comfortable and labor-saving way.

## 1. Introduction

Road, traffic, and environmental information are needed to inform the safe driving of a car. Drivers need to obtain, process, and utilize external information so as to operate the car correctly. Statistical analysis has proven that about 80% of driving information is obtained by visual observation [1]. Therefore, the visual cues that drivers use to control their speed and heading, and how they search for gaze targets, are of great significance when modeling and predicting the variation tendency of eye movements executed in naturalistic driving tasks, as well as in order to understand driving behavior.

For decades, much work had been done to investigate drivers' visual characteristics in naturalistic tasks by real and simulated methods [2–8]. Visual strategy and the distribution of fixation points when driving on bends are one of the most extensively studied aspects. Due to the subject's gaze behavior being closely bound to task conditions, both in spatial and in temporal terms, a perfect theory or model that can be used in any situation is hard to derive [6–8].

Until now, three main classes of driver eye-movement models had been proposed. The tangent-point hypothesis was

the first to be put forward and had been the most popular to date [9–12]. The tangent point is the point in the driver's visual field where the apparent visual orientation of the inside lane edge or road shoulder is reversed. Researchers argued that road alignment and curvature information could be revealed by this critical point and that drivers would depend on this information to control the steering of the vehicle. According to steering angle feedback, the tangent-point model was divided into a tangent-point targeting model and a tangent-point orientation model. In the former, drivers fix their gaze on the tangent point and use its visual angle relative to the locomotor axis to judge the curvature of the bend. This model makes no specific prediction about the driver's steering. In the latter model, drivers fix their gaze on the tangent point and actively steer so as to keep the visual angle of the tangent point in a constant horizontal direction.

The second class of models assumed that the gaze targets when driving around curves are points on the future path, parts of the road surface that the driver intends to pass over [13–19]. These points are near to the tangent point but not necessarily the tangent point, which is tracked because it provides preview information about the road alignment.

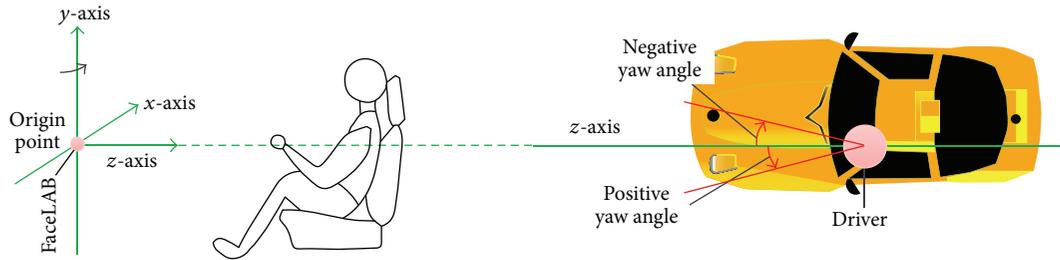


FIGURE 1: The car-fixed coordinate system for the driver's eye movements.

Drivers fix their gaze on this point and then steer so that the target point sweeps from its initial offset to directly in front of the vehicle's true heading, at a constant rate. Some researchers holding this opinion had further investigated the relation between target points and vehicle's handling stability, reaching the conclusion that the driver's gaze concentrates on the part of the road where the vehicle's yaw rate will be the highest. Furthermore, many researchers had posited that the tangent point's orientation is mainly a result of the contiguity of the future path reference points and the tangent point.

The third class of models was based on the view that the far zone beyond the tangent point is an important gaze target area during steady-state cornering [20]. In this model, the single fixation point transforms into a region. This model is in line with the future path steering angle but is difficult to reconcile with any pure tangent-point steering model.

The three kinds of drivers' eye-movement models did reveal drivers' visual characteristics when driving on bends to some extent. They all suggest that some geographical point or zone is the driver's gaze target, but there is no consensus on whether the actual gaze target is the tangent point itself, or some other road points in its vicinity, nor on what the functional significance of target-point targeting or target-point orientation might be.

Therefore, for this paper, research was carried out to continue the investigation of drivers' eye movements, gaze strategies, and the distribution of the fixation points. Talented participants were asked to drive the experiment vehicle on appointed tortuous routes so that eye movement and vehicle driving parameters could be collected. The resulting data were analyzed and some interesting phenomena were discovered. It appeared that the drivers fixed their gaze on the left road edge when driving around both left- and right-hand bends. The gaze direction fluctuated around the reference axis and the fixation points were spread through the region centered on the horizontal gaze position, rather than any geometrical points. Combining the traffic rules in China with these results, we suggest here that there is no particular point on which a driver concentrates. Any point or position that could indicate the bend curvature could be the so-called target point. Drivers just want to operate their vehicles so that they pass around bends safely in a comfortable and labor-saving way.

## 2. Method and Materials

**2.1. Data Collection Method.** Drivers' visual and vehicle-steering performances were measured using a Benz car equipped with instruments to record and store information on the gaze direction, eyeball position, angle of the steering wheel, driving speed, and other parameters. The FaceLAB device that can collect the position of the driver's head, eyeballs, and pupils, as well as the gaze direction, was installed on the dashboard, just in front of the driver, as shown in Figure 1. Sampling frequency for FaceLAB is 45 Hz–65 Hz, while acquisition accuracy is 0.1 degree. A camera was fixed in front of FaceLAB to record road, traffic, and environmental conditions ahead of the vehicle. The logged videos would be used to determine the second-by-second driver fixation targets and analyze the information the driver obtained visually while driving. To ensure that the video could reflect driver's visual range and fixation targets precisely, the camera was placed at the same height as the FaceLAB stereo head frame, pointing straight ahead.

To aid the description of driver eye movements, a coordinate system was established. The installation position of FaceLAB was labelled the origin of the coordinate system, with the  $x$ -axis pointing to the right of the driver, the  $y$ -axis perpendicular to the  $x$ -axis and pointing upwards, and the  $z$ -axis perpendicular to the  $xy$ -plane and pointing at the driver, as shown in Figure 1.

Traffic and environmental information that catch driver's attention can be divided into two parts: the part along the  $x$ -axis, that is, in the horizontal direction and the part along the  $y$ -axis, that is, in the vertical direction. Typically, most of traffic information is distributed in the horizontal direction, with quite a small amount in the vertical direction. However, traffic signs are mainly distributed in the vertical direction and provide necessary information for driving. While traffic signs are necessary driving information and drivers must look at them in driving, it is assumed that drivers have nearly no difference in searching for or looking at traffic signs. Therefore, drivers' eye movements in the horizontal direction are the most important, as drivers pay most attention to this when driving. For convenience of analysis and expression, the angle between the  $z$ -axis and the gaze direction vector is defined as the horizontal gaze yaw angle and labelled as H-yaw angle in this paper. The H-yaw angle is positive when the gaze direction vector is to the left of the  $z$ -axis, and vice versa.



FIGURE 2: The left-hand bends (map obtained from Google Earth).

VBOX equipment was used to collect the vehicle driving parameters, such as driving speed, steering angle, brake force, lateral acceleration, yaw rate, and roll angle. Sampling frequency for VBOX is 20 Hz, and the acquisition accuracy of vehicle location is 1.8 m.

**2.2. Subjects and Routes.** Ten subjects participated in the experiment. All were males and aged from 27 to 55 years old. They all held a valid driving license and had sufficient driving experience (had been driving for at least 8 years). Conditions for inclusion in the experiment were normal uncorrected vision (qualified to drive a car without guidance and did not depend on glasses) and driving the same vehicle daily. All participants had to be naïve to the relevant theories on drivers' visual characteristics (the tangent-point orientation model, the future path model, the bend curvature and yaw angle dependence model, etc.).

Two tortuous roads were picked out as the test routes. Each road was a high-standard urban road with normal traffic density. On both routes, the number of lanes differed in different road sections. The total length of the first route was 21 km and that of the second was 14 km. Two left-hand bends (one-way traffic) located on a flyover were included in the first route; the cornering sections are shown in Figure 2. A typical cloverleaf interchange is included in the second route and there are four right-hand bends (one-way traffic), as shown in Figure 3. The left- and right-curving sections are labelled as L1, L2 and R1–R4 in this paper.

All drives were carried out in daylight and peak traffic periods were avoided. For each subject, preliminary experiments were executed twice on both routes to avoid instrument failure, route confusion, and the tense mood. Obtaining route directions and guidance on vehicle operation was forbidden during the actual driving experiment. Official experiments were conducted three times for each participant on both routes to ensure that drivers' visual parameters and vehicle-driving parameters of a high quality were collected and stored.

As VBOX registers vehicle driving parameters by relying on a satellite signal, the quality of data collection will decrease when the satellites signal was cut off, such as the car drives under bridge. Since our research is limited to curved sections,

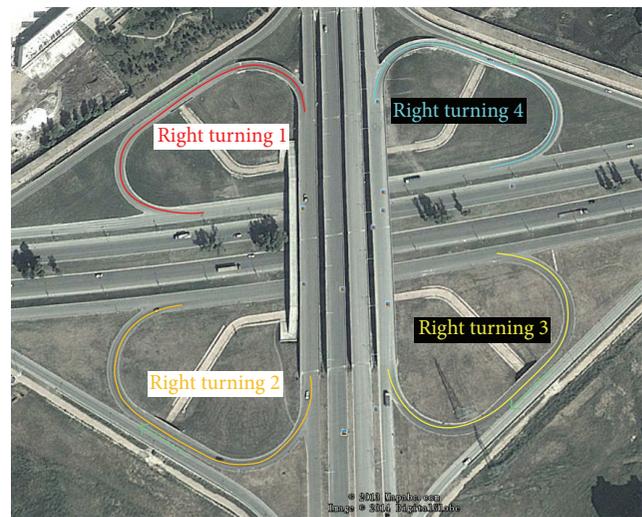


FIGURE 3: The right-hand bends (map obtained from Google Earth).

none of which pass under bridges, this phenomenon does not affect our experiment.

From the experiment, 30 sets of high-quality data were obtained for each route to be utilized for data analysis and the investigation of the phenomenon. Due to the large amount of data and unexpected road sections, data segments during curve negotiation were separated from the overall data. To capture the entire phenomenon of curve driving, the entry, cornering, and exit parts of the curves were all included.

The FaceLAB and VBOX instruments use different timing modes (computer time for FaceLAB and UTC time for VBOX), and they have different frequencies of sampling (45 Hz–65 Hz for FaceLAB and 20 Hz for VBOX). Thus, time synchronization was needed to ensure that the eye and vehicle parameters had the same time scale. Limited by the VBOX sampling frequency, the two kinds of parameters were synchronized to 0.05 s.

### 3. Analysis of Drivers' Eye Movements

**3.1. The Correlation of the Driver's Gaze Trajectory and the Steering Angle.** The original gaze records showed a typical

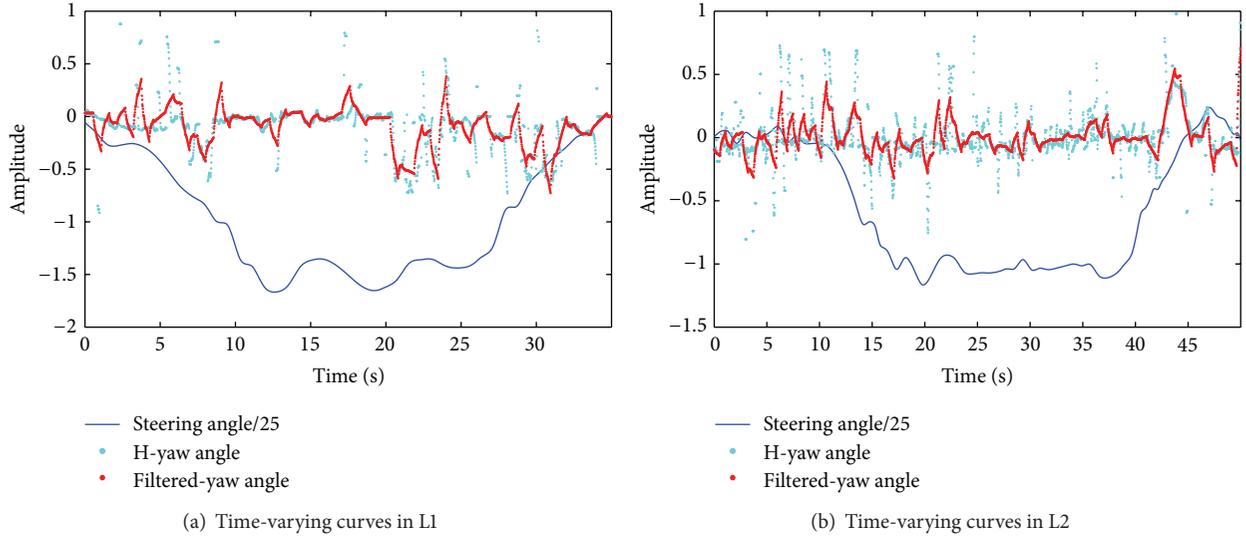


FIGURE 4: Steering angle and driver's gaze direction when driving around left-hand curves.

pattern of saccades, fixations, and smooth tracking. Fixations and smooth tracking are more salient for revealing drivers' gaze targets and areas of interest. Saccades occur between two fixation points and indicate the visual search trajectories of the driver. Limited by measuring range of FaceLAB, measurement signal would suffer distortion. Therefore, wavelet filtering was applied to the original gaze records to remove noise interference and obtain the pure fixation signals.

Depending on the filtered gaze records and the time synchronizing of the two types of parameters, the vehicle steering angle relative to the locomotor longitudinal axis (the true heading) and the driver's gaze direction towards the visual targets obtained from one typical experiment were compared with each other, and their time-varying curves were presented in Figures 4 and 5. All of the ten participants showed similar behavior. As the amplitude of the steering angle is much bigger than that of the H-yaw angle, the steering angle was reduced in scale to make the comparison clear; the scale of the reduction was specified in the corresponding parts of Figure 5.

An interesting finding emerged from the comparison of the steering angle and the H-yaw angle. Unlike the conclusion drawn from the *tangent-point orientation theory* that the simultaneous records of gaze direction and vehicle steering angle have quite similar variation tendencies, with the steering wheel turned at an angle corresponding to the direction of the gaze relative to the car's heading, after a delay of about 0.75 seconds, the relation between the gaze direction and the steering angle is no longer so apparent in this paper. During the cornering process, the steering angle changes when the vehicle drives on different cross sections of the curved section, as shown in Figures 4 and 5. However, the overall variation trend of the gaze direction was not clear.

It can be seen from the figures that the driver's gaze direction keeps returning to the reference axis during the entire process of driving around the curve. The transfer of attention of the subjects was presented as a form of smooth

TABLE 1: Percentages of positive H-yaw angles and of large H-yaw angles in the cornering process.

Road section	L1	L2	R1	R2	R3	R4
P-percentages (%)	46.22	47.45	53.96	43.21	48.64	66.23
L-percentages (%)	0.3124	0.5333	0.2753	1.1899	0.5250	0.9138

tracking. It appears that the drivers were searching for something purposely. Furthermore, the absolute maximum H-yaw angles on both sides of the  $z$ -axis were approximately equal. The fluctuation of the gaze direction around the reference axis during both the left and the right turning periods was almost equally distributed. As the gaze direction is defined and measured in car-fixed coordinates, the barely changing gaze direction indicates that the driver's gaze direction is in line with the vehicle's true heading, that is, the locomotor longitudinal axis, as shown in Figure 6. Thus, the driver's area of interest and concern when engaged in curve driving was mainly distributed in the region around the horizontal gaze position. The horizontal gaze position is the fixation location when the driver keeps his eyesight at the horizontal level and keeps looking straight ahead. It is easy to see that the horizontal gaze position is parallel to the  $z$ -axis, as shown in Figure 7.

To determine the distribution of the H-yaw angle, a preliminary statistical analysis was carried out in order to obtain the levels of the positive and negative H-yaw angles. The percentages of the positive H-yaw angle, which are labelled as P-percentages, were listed in Table 1. It can be elicited from the analysis results that the drivers' gaze targets when driving around curves are concentrated in the region of the horizontal gaze position, over a range of a few degrees. The subject's focus stays fixed in the straight ahead direction, that is, in the direction in which the vehicle is moving. According to SAE J1050, in order to look at targets clearly and judge their size and position accurately, a driver will need to turn his

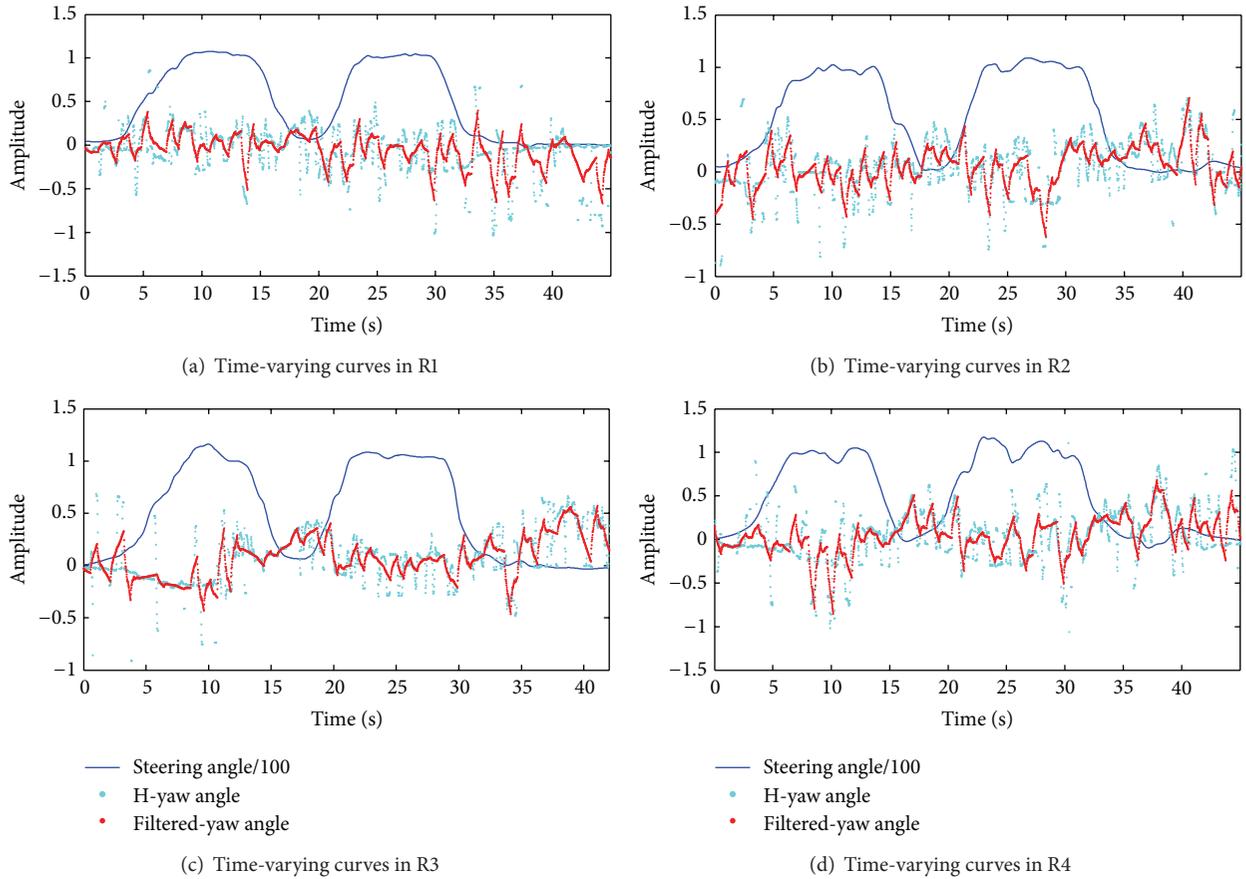


FIGURE 5: Steering angle and driver’s gaze direction when driving around right-hand curves.

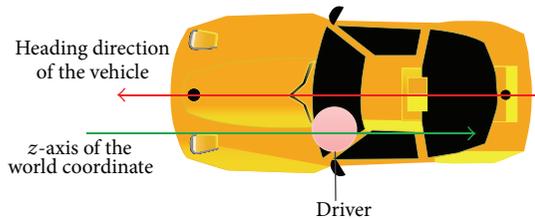


FIGURE 6: Vehicle’s true heading.

head when the H-yaw angle is greater than 0.26 radians (15 degrees). Thus, the number and percentage of H-yaw angles whose absolute values are greater than 0.26 radians were also measured in order to monitor the probability distribution of the H-yaw angle and situations in which the driver must move his head. The levels of the large gaze vector, which are labelled L-percentages, were also listed in Table 1. The calculation results showed that the large yaw angles make up less than 2% of all the H-yaw angles on both the left- and the right-hand bends, which indicates that the driver hardly turns his head when cornering and just focuses on the road, the traffic, and the environmental conditions straight ahead.

Turning the steering wheel causes a change in the vehicle position and determines the true heading. While the gaze direction was defined and measured relative to the true



+ Horizontal gaze position  
• Gaze position

FIGURE 7: Driver’s horizontal gaze position.

heading using the car-fixed coordinates, a coordinate transformation can be performed to convert the gaze direction from the car-fixed coordinate system to the earth-fixed coordinates, giving the results shown in Figure 8. It is quite obvious that the variation trend and the changing frequency of the gaze direction and the steering angle are consistent with each other. Therefore, a fluctuating curve around the zero point of the gaze direction produces consistency in the gaze

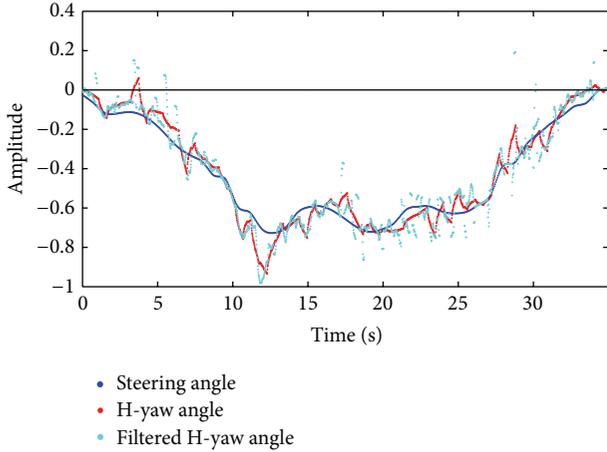


FIGURE 8: Gaze direction in the earth-fixed coordinates.

direction and the vehicle's true heading, that is, agreement of gaze direction and steering angle.

### 3.2. The Distribution of Fixation Points and Area of Interests.

The subjects' gaze behavior and visual characteristics are closely bound to the task conditions, both in spatial and in temporal terms. Subjects search for task-relevant gaze targets in order to inform their operation of the vehicle and to drive safely and appropriately. In addition, gaze target selection is closely linked to the execution of complex driving tasks in different phases. Correct gaze targets must be picked out just in time to be verified and manipulated so as to meet the demands of driving the car. Therefore, where participants look and what they pay attention to and search for need to be verified based on real-life and detailed videos.

The changing trend and distribution of the drivers' gaze direction when driving on curves were investigated and analyzed in Section 3.1. The conclusion was drawn that almost all of the drivers' H-yaw angles were smaller than 0.26 radians and that the areas of interest (AOIs) to which drivers pay attention centered on the horizontal gaze position. However, the reason for this finding cannot be determined by relying on time-varying curves alone. The gaze targets during every second of a particular driving task need to be determined.

To investigate the gaze targets and the distribution of AOIs for drivers driving carefully and accurately around curves, fixation points were derived from the original eye-movement parameters. They were plotted on the corresponding foreground image, illustrating the real-time road, traffic, and environmental conditions ahead of the vehicle. A representative left-turning curve was selected and the distribution of fixation points in each second of the driving period was presented in Figure 9. The white cross shows the driver's estimated horizontal gaze position and the cyan cross shows the tangent point.

It is quite obvious that, similar to the view of tangent-point orientation theory, most of the fixation points are spread along the inside road edge and the drivers focus on the road alignment. However, during cornering, the driver's horizontal gaze position is quite close to the tangent point, as shown in Figure 9. Therefore, whether the subjects were

gazing at the tangent point or just looking straight ahead could not be judged. A more careful observation revealed that, different from the tangent-point and the future-path models, the AOIs of the subjects are below the tangent point and spread in the nearby zone adjacent to the tangent point (Near Zone), as shown in Figure 10. While most of the fixation points are located in the Near Zone, which is below the tangent point, the preview distance is shorter than that determined in the preview theory [21, 22]. The preview distance is the distance from the vehicle to the gaze targets. In light of the small steering angle when driving around left-hand curves (about 35 degrees), we need more evidence to make a decision about the exact gaze target.

The distribution of fixation points on the right-hand bends was presented in Figure 11. The white and cyan crosses represent the driver's horizontal gaze position and the tangent point, respectively. Fortunately, in the right-turning curves, the distance between the horizontal gaze position and the tangent point is big enough for them to be distinguished from each other. Furthermore, unlike the discovery for left turns, the fixation points of the participants are located on the outside of the road edge in this case. As shown in Figure 12, most of the fixation points are distributed on the part of the road surface that is visible in the far-left quadrant (Far Zone). The AOIs when driving around right-hand curves are above the tangent point which indicates that the preview distance is larger than that determined in the preview theory [21, 22].

According to the above investigation and analysis on both left- and right-turning curves, it was drawn that the driver pays attention to the left side of the road in curves driving. In China, drivers drive on the right and the left is used for overtaking. Therefore, the traffic conditions on the left side are much more complicated and important. To drive safely and manipulate their vehicles appropriately, drivers need information on their left side. Therefore, it may be that the traffic rules and the driver's position in their car contribute to the above findings. In left-turning curves, the vehicle's driving direction intersects with the inside road edge and the fixation points are distributed near the tangent point (which still cannot be determined in light of the blurriness between the horizontal gaze position and the tangent point). In right-turning curves, while the vehicle's driving direction still intersects with the inside road edge, the fixation points are located on the opposite side. Hence, there is reason to doubt the tangent-point orientation theory. The oft-reported "tangent-point orientation" may in some cases be a side effect caused by the spatial contiguity. As the center of the AOI could explain the driver's visual search patterns and elicit information about the objects on which drivers focus, it is of great significance. Combining the conclusions drawn in [9–12] with the discoveries made in this research, the horizontal gaze position and the tangent point were picked out as the centers of the AOIs. The percentages of fixation points in AOIs centered on the tangent point and the horizontal gaze position, respectively, with different sizes, were calculated as follows:

$$\text{percentage} = \frac{1}{m} \left( \sum_{j=1}^m p \right), \quad (1)$$



FIGURE 9: The distribution of fixation points in the left-turning process.

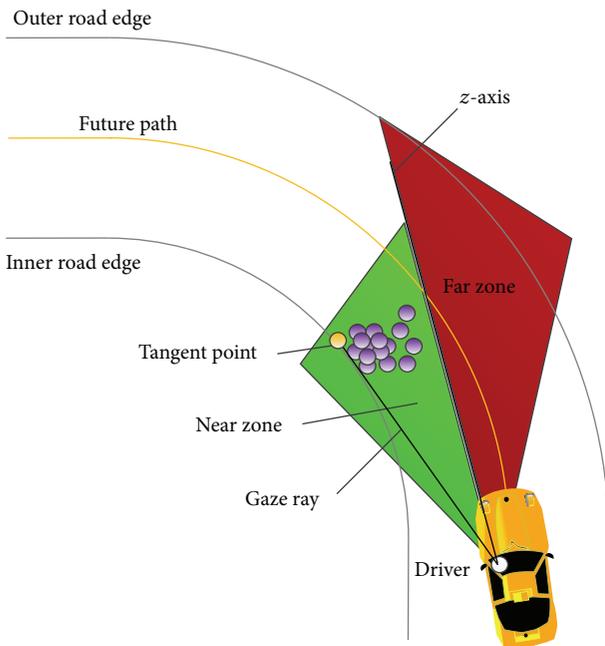


FIGURE 10: AOIs in left-turning curves.

where  $m$  is the total number of seconds the vehicle spends in the entry/exit parts and the cornering parts of all of the right and left curves and  $p$  is the share of fixation points in the AOIs in each second.

The percentages of fixation points in the entry/exit parts and the cornering parts were calculated separately.

The percentages of fixation points in AOIs centered on the tangent point and the horizontal gaze position with different sizes were presented in Figures 13 and 14. Based on the description of the human eye diopter, when a subject focuses on an object and can determine its size and position, the visual angle is not bigger than 25 to 30 degrees. The limiting

value differs from person to person. Hence, the maximum degree for the AOIs is set at 10 degrees, and the step size is set at 2 degrees.

In left turns, when the size of the AOIs is 2 degrees, more fixation points distribute in the area centered on the horizontal gaze position. The analysis results for the entry and exit phase and the cornering phase were the same. It can be seen from Figure 13 that at least 20% of the fixation points are spread in the region centered on the gaze position with a size of 2 degrees. As the size of AOIs increases, the two kinds of percentages overlap with each other and both of them increase. Still, most of the values based on the horizontal gaze position centered AOIs are bigger than those based on the tangent point centered AOIs.

Besides this, the smaller the size of the AOIs is, the greater the aggregation degree of the fixation points is. Therefore, the share of fixation points in the AOIs with size of 2 degrees is much more important and more attention should be paid to it. According to the statistical analysis, in left-turning curves, fixation points centered on the driver's horizontal gaze position are much more appropriate than those centered on the tangent point.

In right-turning curves, the distribution of fixation points centered on the horizontal gaze position is much more apparent, as shown in Figure 14. No matter how big the size of the AOIs is, the percentages of fixation points located in the circle centered on the horizontal gaze position are all larger than those centered on the tangent point.

**3.3. Discussion.** Almost certainly, the driver concentrates on the road alignment when driving around curves so as to pass through them safely. This hypothesis had been studied and proved by many researchers. However, in this research, using real-time analysis of drivers' gaze targets when driving around curves, it has been found that, in left turns, the driver's fixation points are spread along the inside road edge,

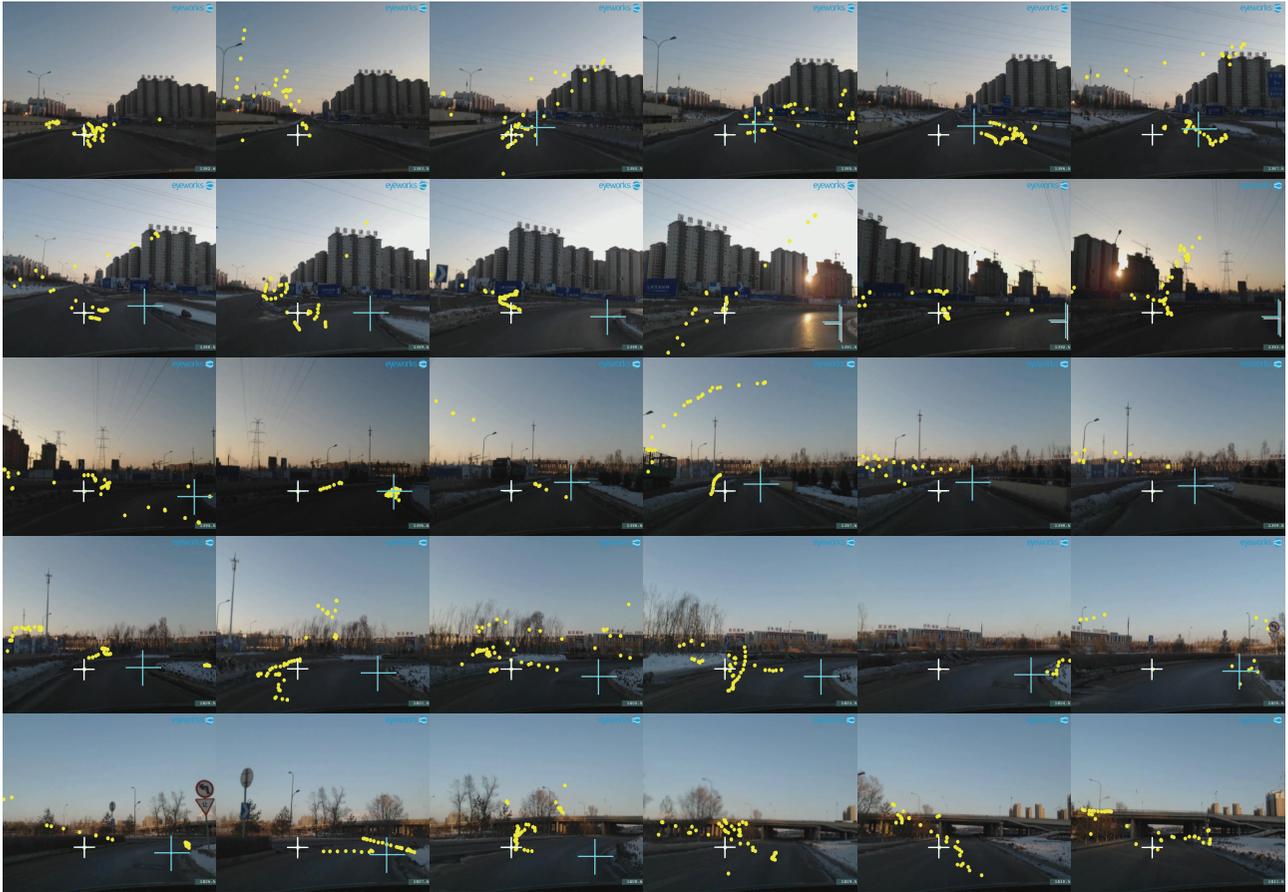


FIGURE 11: The distribution of fixation points on right-hand bends.

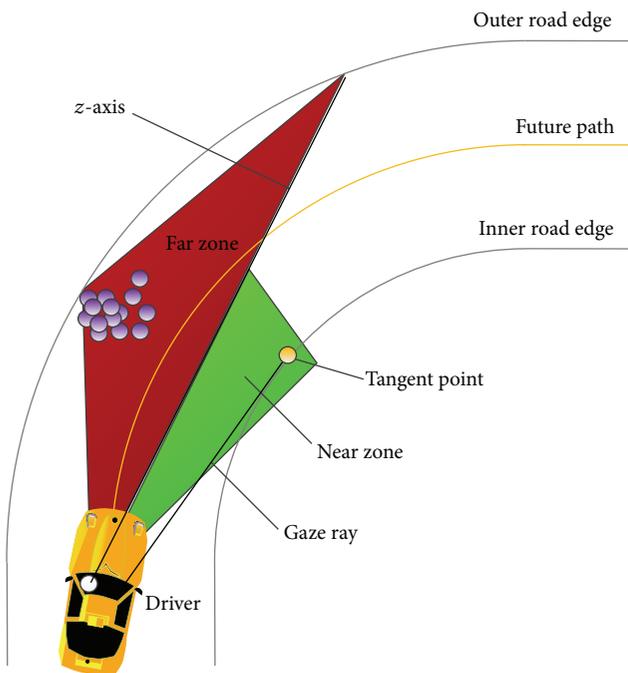


FIGURE 12: AOIs in right-turning curves.

while they move to the outside road edge in right turns. This phenomenon differs from research results from outside of China, where drivers have been found to focus on the inside road kerb in both left and right turns. Besides this, the synthesized foreground pictures and statistical analysis have shown that the driver fixation point is not centered on the tangent point but on the horizontal gaze position. In left turns, the horizontal gaze position is below the tangent point and the preview distance decreases. In right turns, the horizontal gaze position is above the tangent point and the preview distance increases.

In China, vehicles drive on the right and the driver sits on the left side of the vehicle. Therefore, the left-side situation must be verified and managed by the driver and this is more convenient to monitor. The right-side situation is less important and it is more difficult for the driver to have complete control over it. Thus, on left-hand bends, the driver will focus on the left road edge so as to determine the road curvature and the correct steering angle. As the steering angle is small (about 35 degrees in the L1 and L2 left turns in this paper), the angle between the true heading and the vehicle's driving direction is small, and the position when the driver looks straight ahead on the horizontal level is quite close to that of the tangent point. It is labor saving and comfortable for

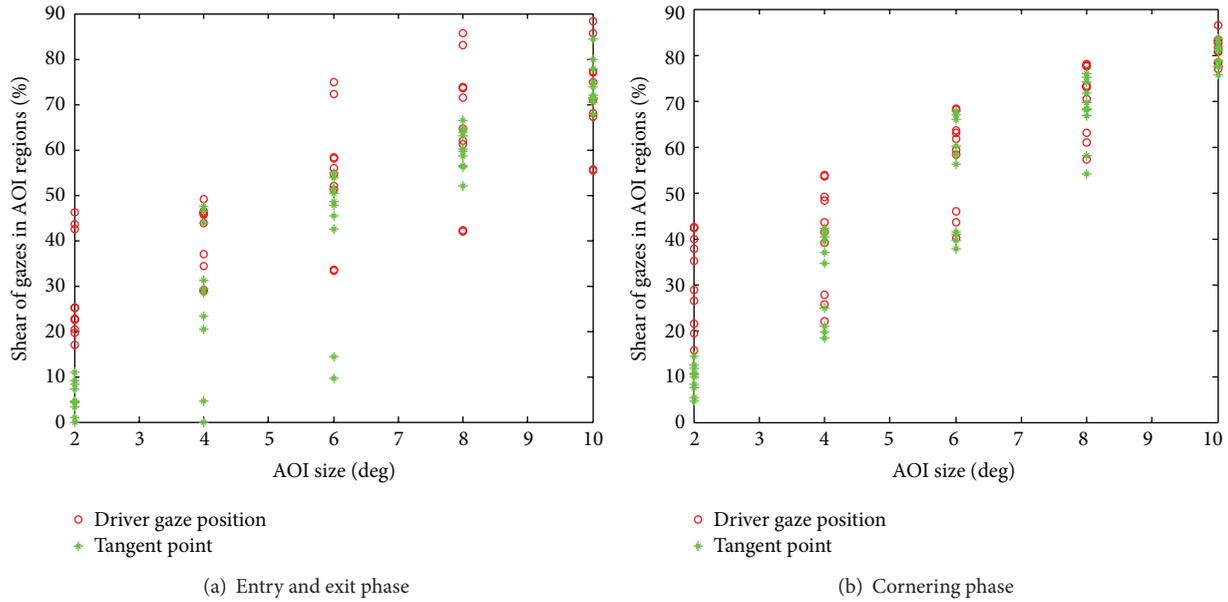


FIGURE 13: AOIs in left-turning curves.

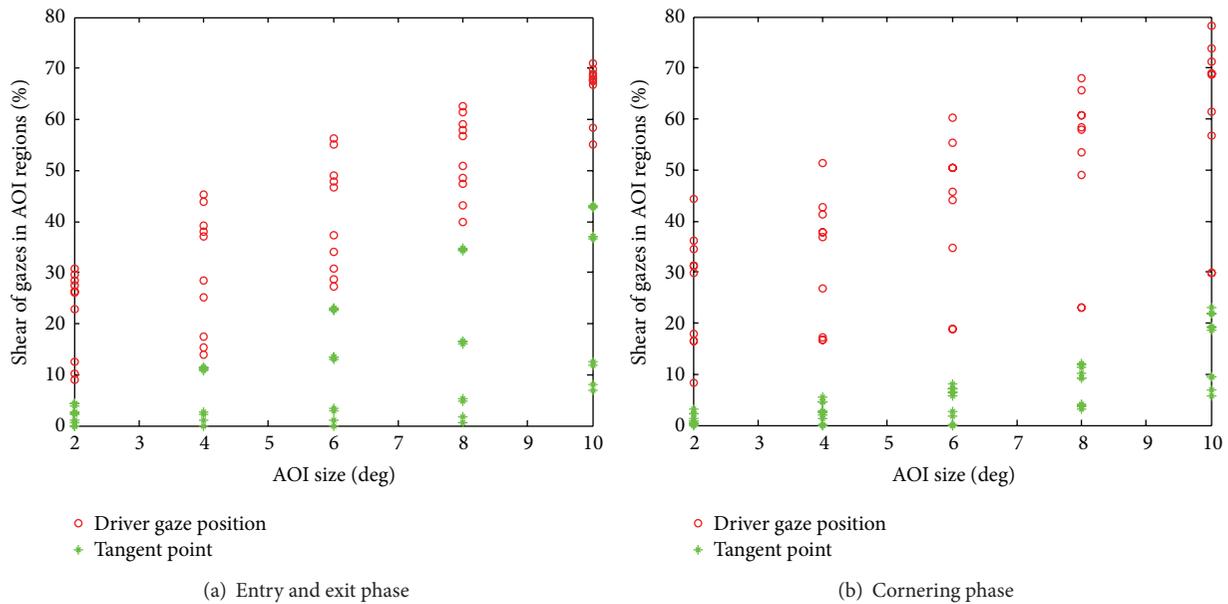


FIGURE 14: AOIs in right-turning curves.

the driver to just look ahead. Hence, driver’s gaze directions are almost equally distributed on both sides of the z-axis. On right-hand bends, although the right road edge shows the curvature of the bend, taking information from both sides of the road places a big burden and requires the driver to turn his head from side to side. Thus, the driver gives up on the right side and focuses on the left side of the road, which also expresses the bend curvature.

According to the above analysis, it can be concluded that drivers operate their vehicles in a way that is comfortable and labor saving.

#### 4. Conclusions

Drivers’ visual strategies, gaze targets, and fixation point distributions are salient for determining the visual information management of drivers and predicting their driving intentions. Much research had been done on this subject and models of tangent-points, future paths, reference points, vehicle yaw angles, and so forth had been quite popular. All of the previous studies had focused on a specific point that the driver pays attention to, and researchers have tried to draw conclusions based on the geographic position of that particular point. However, there is still no consensus

on which point is the gaze target and what functional significance that point might have.

Similar research has been done in this paper to investigate drivers' visual characteristics. Ten talented participants were employed to drive the experiment car on appointed tortuous routes. Drivers' eye movements and vehicle driving parameters were registered in the experiment. Particularly, left- and right-hand bends were analyzed.

The data analysis showed that the driver's attention focuses on the left road edge in both left and right turns. The driver's gaze direction fluctuated around the reference axis and fixation points were distributed in the region centered on the horizontal gaze position rather than a particular point that has geographical meaning. Combining the traffic rules in China with the results of our experiment, we suggest here that there is no particular point on which drivers concentrate. Any point or position that could indicate the bend's curvature could be the so-called target point. Drivers just want to operate their vehicles so as to pass through bends safely and in a comfortable and labor-saving way.

While experiment data only could show the results of vision-guidance in curves driving, mental research should be carried out to command the drivers' real idea.

## Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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