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Using 3D Mobile Mapping to Evaluate Intersection Design Through Drivers' Visual Perception

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ABSTRACT At intersections, road features related to different maneuvers, such as left-turn, right-turn, and central channelization (i.e., guidelines and channelized islands), are widely used to decrease the traffic conflicts and improve the safety and mobility of traffic. However, there are several main problems related to channelization design at intersections, including poor recognizability, unreasonable entering speed, insufficient sight distance, and relatively low merging speed. To address these problems, this paper focused on developing a method to assess how to design intersection features by dividing the driving process through intersections into four stages: "appearance of channelization," "beginning of channelization," "middle of channelization," and "end of channelization." Drivers' visual lane models were established based on the Catmull–Rom spline to quantify visual road information perceived by drivers. Shape parameters and three characteristic regions were extracted from these models. The naturalistic driving experiments and 3D mobile mapping experiments were conducted at intersections with channelized islands or guidelines. Driving speed distributions in the four stages were found to obey normal distributions and could be calculated by shape parameters with Bayesian inference. Then, 3D mobile mapping was used as a substitute for extensive naturalistic driving experiments to obtain drivers' visual perception from all possible visual angles. An evaluation method on intersection design was built and used to identify which stage of channelization needs to be modified. This new method helps to enhance the safety and efficiency of intersections.

INDEX TERMS 3D mobile mapping, intersection design, channelization, drivers' visual lane model, Bayesian inference.

I. INTRODUCTION

Intersections are widely recognized as one of the most dangerous locations in a roadway network due to the crossing traffic streams [1], [2]. For example, about 30% of fatal crashes and 50% of injury crashes occurred at or near an intersection in the United States [3]. In Canada, crashes related to intersections also accounted for over 30% of the fatalities and 40% of the severe injuries [1]. Likewise, around 30% of the total crashes were attribute to intersections in China [4]. To decrease the traffic conflicts, channelization (i.e., guide lines or channelized islands) is one of the popular intersection designs [5]. This kind of intersection design can reduce the number of crashes and improve the mobility of traffic [6], [7]. However, the effectiveness will be greatly reduced when the channelization design is poor.

There are four main channelization problems: 1) poor recognizability, 2) unreasonable speed for vehicles entering the channelization, 3) insufficient sight distance, 4) large speed differences between vehicles and the destination traffic stream [8]–[11]. More specifically, poor recognizability means that drivers cannot detect the guide lines or channelized islands in time when approaching the intersection, so they cannot timely take a right action to reduce their speed. Unreasonable entering speed represents the driving speed when entering the channelization is not stay in an appropriate range. If the entering speed is too high, the vehicle may crash into the curbs or run into the adjacent lane, while with a

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too low entering speed, a rear-end crash is more likely to occur. Insufficient sight distance shows the drivers cannot see far enough and their visual field is blocked by trees, a large curve, etc. in the process of passing the channelization, so high volatility of driving speed may lead to the decrease of safety and efficiency. Relatively low merging speed into the destination traffic stream significantly affects the likelihood of rear-end crashes and the mobility of traffic.

To date, studies of channelization mainly focus on the process of driving through channelization, with evaluation metrics like collisions, conflicts, etc. This approach is not ideally suited for studying the four major problems and understanding the inner structure of channelization. Unreasonable planning of driving speed is mainly responsible for these four main issues. During the driving process through channelization, drivers first perceive road information visually and then determine driving speed. Some researchers have identified a discrepancy between actual and perceived geometric alignments [12]. In addition, drivers have a range of visual angles, so a new channelization evaluation technique is needed to explore the range of drivers' visual angles. Thus, the purpose of this study is to provide a new evaluation method for channelization design through drivers' visual perception based on 3D mobile mapping.

II. LITERATURE REVIEW

Many scholars have researched right-turn, left-turn, and central channelization at intersections. This foundational work has established and advanced the analysis and evaluation methods used in this area.

Right-turn channelization separates the turning vehicles from the through traffic movement and offers space for deceleration [13]. Channelized right-turn lanes can be defined as turning paths at intersections that provide for nearly free-flow right-turn movements [9]. Al-Kaisy *et al.* [14] analyzed the driver's behavior at channelized right turn lanes with raised (curbed) islands in southwest Montana, and results showed that more than 50% of the drivers who used the channelized turn lane regarded the traffic signal as a yield control. After investigating driving speed at 19 urban channelized right-turn lanes, Fitzpatrick *et al.* [13] found that different channelization methods (a lane line or a raised corner island) and sizes (channelization radii) had an impact on the 85th percentile free-flow vehicle speed. A new channelized right-turn design called Smart Channels was proposed by Zegger [15], which reduced the angle of the channelized right-turn to around 70°. This provided drivers with a broader visual view of the traffic flow for merging into the destination traffic stream. Sacchi and Sayed [16] put forward a conflict-based, before–after (BA) safety evaluation of Smart Channels, and then compared it with a collision-based BA evaluation method.

In China, when most left-turning vehicles enter an intersection without channelization, many vehicles often change their driving routes, because drivers want to enter the target lane directly or as soon as possible for psychological reasons [17]. This leads to chaotic driving and severe conflicts between vehicles. Channelization islands in the left-turn lanes can reduce the crash risk and enhance vehicle movements through an intersection [18]. Cooner *et al.* [19] proposed the idea of adding guide lines for triple left turn intersections in Texas. Wei *et al.* [17] extracted features of left-turning vehicles' trajectories and set left-turning guide lines at intersections. They found that with left-turning guide lines, the average driving speed could be improved and the average driving delay decreased. To separate potential vehicle conflicts, unconventional intersections use wide median U-turns to replace left turns from the main intersection [20]. U-turn intersections are designed with channelizing and splitting islands to offer increased protection during U-turns [21].

A roundabout is an unsignalized intersection where traffic moves one-way around a central channelized island [22]. Many intersections have been changed into roundabouts in both urban and rural areas, because roundabouts have advantages in safety and mobility [23] [24]. Robinson *et al.* [25] concluded that injury accidents on single-lane intersections decreased by 73% with roundabouts. On multilane roundabouts, the number of injury accidents declined by 31%. Owing to the omission of left turns, roundabouts had a greater traffic capacity [26]. A central channelized island could be safer if its diameter was greater than 10 m [27]. To further prevent traffic from weaving, Wang *et al.* [28] presented a novel method for improving the center island design based on the spiral-shaped driveways.

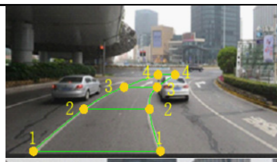
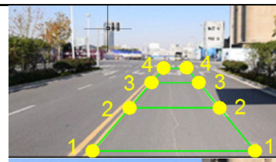
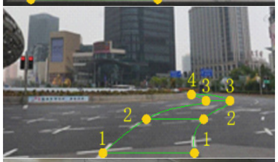
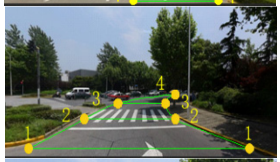
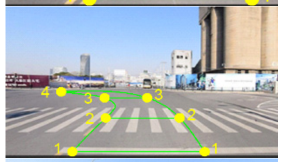
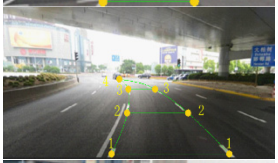
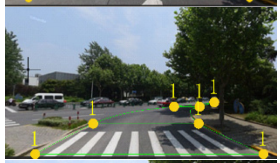
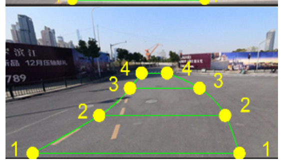
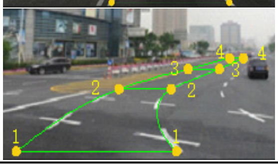
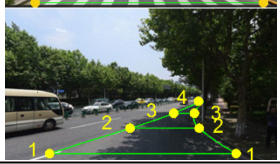
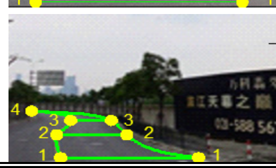
As seen in the work summarized above, previous studies analyzed and evaluated channelization design mainly from the perspectives of traffic conflicts, road collisions, travel time, driving delays and so on. Less attention was paid to the channelization design itself to consider whether the geometry of channelization design is appropriate and satisfies drivers' needs. Current evaluation methods mostly regard the channelization driving process as a whole, and there is a lack of studies that explore the inner structure of this process. Some scholars [29] also pointed out that drivers expected and anticipated certain geometric and operational situations at intersections, and the channelization should be aligned with these expectations as closely as possible. Thus, this paper aims to present a new evaluation method for channelization design through drivers' visual perception.

The remaining parts of this paper are organized as follows: The next section presents a description of the driver's visual lane model, four stages of channelization, naturalistic driving studies, and 3D mobile mapping experiments. In Section 3, driving speed distributions in Four stages are calculated, visual information from different visual angles are obtained by 3D mobile mapping, and a new evaluation method on channelization is provided. Then, Section 4 gives the discussions and conclusions.

III. METHODOLOGY

This Methodology section consists of three parts: (1) Establishing a drivers' visual lane model to quantify visual road

TABLE 1. Four stages of different channelization.

Stages	Central channelization	Right-turn channelization	Left-turn channelization
Appearance			
Beginning			
Middle			
End			

geometry features perceived by drivers; (2) Dividing the driving process through channelization into four key stages; (3) Using naturalistic driving experiments to calculate the speed distributions and 3D mobile mapping experiments to acquire drivers' visual perception from different visual angles.

A. DRIVER'S VISUAL LANE MODEL

During the driving process, a "lane" exists in drivers' visual field at all times. Even in the absence of lane markings, drivers can perceive the shape of a "lane" according to the specific situations and use this to guide driving behavior. This "lane" can be described as the drivers' visual lane model based on the Catmull-Rom Spline [30]. The validity of drivers' visual lane model in quantifying drivers' visual perception has been demonstrated [31].

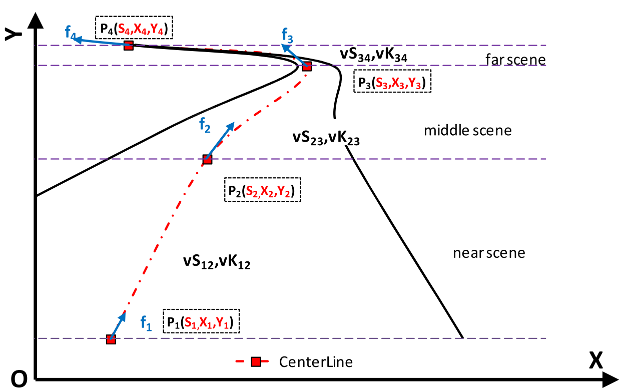


FIGURE 1. Drivers' visual lane model.

In Figure 1, the bottom-left corner in drivers' visual field is set as the origin. There are four control points (P_1, P_2, P_3, P_4) in Catmull-Rom spline. Locations of control points are determined by the shape of Catmull-Rom Spline, so positions of control points change when drivers' visual lane models change. Four horizontal lines pass through four control points and divide drivers' visual field into three characteristic regions - namely, "near scene," "middle scene" and "far scene." Curve length and curvature of visual lane centerline in three regions are chosen as shape parameters of drivers' visual lane model, denoted by $[vS_{i(i+1)}, vK_{i(i+1)}]$ (i = 1,2,3), and computation formulas are as follows:

$$vS_{i(i+1)} = S_{i+1} - S_i \tag{1}$$

$$vK_{i(i+1)} = \frac{f_{i+1} - f_i}{vS_{i(i+1)}} \tag{2}$$

where, i = 1,2,3; $vS_{i(i+1)}$ denotes visual curve length between control point P_i and P_{i+1} (pixels); $vK_{i(i+1)}$ denotes visual curve curvature between control point P_i and P_{i+1}, namely, the unit rate of change of tangential angle (radians); f_i is the tangential angle at control point P_i(radians); S_i is visual curve cumulative length at control point P_i(pixels).

B. FOUR STAGES OF CHANNELIZATION

The driving process through channelization can generally be divided into four stages: "appearance of channelization," "beginning of channelization," "middle of channelization," and "end of channelization." The "appearance of channelization" stage is defined as the interval when the channelization enters the drivers' visual field. The "beginning of channelization" stage includes the drivers' approach and entry to channelization feature. The "middle of channelization" stage is the period of time the vehicle spends in the channel. The "end of channelization" stage happens when the vehicle departs the channel and merges into the destination traffic stream. Table 1 illustrates the four stages for each type of channelization (central, right-turn and left-turn). These four stages also correspond to the four problems presented in the Introduction, respectively.

C. EXPERIMENTAL PROCEDURE

Naturalistic driving and 3D mobile mapping experiments were conducted to determine driving behavior and the visual information perceived by drivers about channelization. Specifically, naturalistic driving experiments were used to establish the model for speed distributions at key stages of channelization. Then, 3D mobile mapping experiments obtained 3D point cloud information of channelization so that various visual perceptions could be extracted.

Naturalistic driving experiments were carried out in Shanghai, China. A vehicle data recorder (GARMIN GDR35) recorded information in the driver's sightline. The recorder could overcome GPS signal interference to the camera lens and match GPS with driving video information accurately. It recorded the driving location, velocity, three-axis accelerations and a video of the driver's field of view. The information-recording interval was one second. All the information obtained by the recorder was stored as AVI files and a video data processing system was developed to establish drivers' visual lane model. Ten experienced drivers (to eliminate any effect of novice driving behaviors) were selected to conduct the naturalistic driving experiments. The drivers tested ranged in age from 25 to 45 years. Data from driving through left-turn, right-turn and central channelization at a speed of approximately 30 km/h were extracted. This project focused on the geometry of channelization design and did not consider the influence of traffic flow, so only data from a nearly free traffic flow conditions were analyzed. Given this criterion, a sample of 50 events was identified for analysis. The distributions of variables are shown in Table 2. Although the sample size was relatively small, but it was feasible in this study, since Bayesian inference was suitable for dealing with small sample data [32], [33] and these 50 events could provide a general distribution of driving speed. Besides, this study used 3D mobile mapping experiments to obtain much more data from various visual perceptions instead of extensive naturalistic driving experiments.

TABLE 2. Distributions of shape parameters in four stages.

Appearance of Channelization			Beginning of Channelization		
Parameters	Mean	Std.	Parameters	Mean	Std.
vS12	395.81	40.13	vS12	476.94	64.69
vS23	151.39	17.31	vS23	312.85	48.04
vS34	177.16	20.18	vS34	301.77	48.34
vK12	2.74e-4	1.01e-4	vK12	3.08e-4	1.06e-4
vK23	3.94e-3	9.39e-4	vK23	1.08e-3	3.79e-4
vK34	1.36e-3	2.29e-4	vK34	3.55e-4	9.27e-5
Middle of channelization			End of channelization		
Parameters	Mean	Std.	Parameters	Mean	Std.
vS12	618.73	50.55	vS12	584.95	69.74
vS23	360.34	53.62	vS23	382.42	40.62
vS34	407.21	72.72	vS34	401.60	61.55
vK12	4.79e-5	2.71e-5	vK12	1.10e-4	5.19e-5
vK23	4.66e-4	1.10e-4	vK23	3.94e-4	9.07e-5
vK34	2.57e-4	8.19e-5	vK34	1.37e-4	5.24e-5

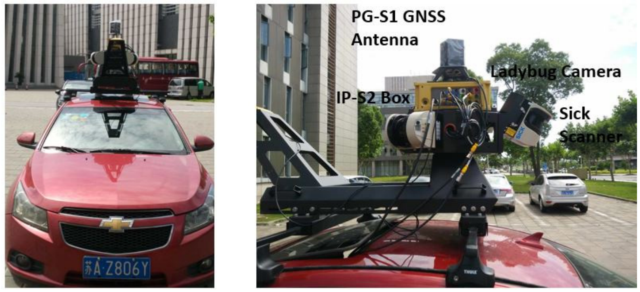


FIGURE 2. Components of the 3D mobile mapping system.

Since drivers had different visual angles, 3D mobile mapping was applied to acquire drivers' visual perception from different visual angles, as shown in Figure 2. The 3D mobile mapping used in this study was TOPCON IP-S2 Compact+ System. It incorporated three Lidar sensors that capture approximately 90,000 points per second, a high-resolution camera, a GNSS positioning module, two symmetrical vehicle wheel encoders, and an Inertial Measurement Unit (IMU) to collect a quick and accurate geo-referenced spatial point cloud of the road environment surrounding the vehicle trajectory. The point cloud data were supplemented with high-resolution panoramic imagery to create detailed 3D models. Based on the 3D point cloud data, drivers' visual lane models from various visual angles were established, and corresponding shape parameters were calculated. Three kinds of channelized intersections located in Shanghai were chosen to for study. For example, the intersection of Binjiang Avenue and Minsheng Road has left-turn channelized guide lines. A right-turn channelized island was built at the intersection of Jinxiu Road and Fangdian Road. While the intersection of Wujiaochang has a large central channelized island.

IV. RESULTS

The evaluation process of channelization can be divided into three steps: (1) using 3D mobile mapping to obtain various drivers' visual perception and establishing drivers' visual lane models; (2) substituting shape parameters that are obtain by 3D mobile mapping into Bayesian inference to calculate driving speed distributions in four stages; (3) plotting recommended speed ranges and evaluating channelization. In the following sections, all the steps will be explained in detail.

A. DRIVING SPEED DISTRIBUTION IN FOUR STAGES

1) DISTRIBUTION CHARATERISTICS

Many scholars have noted that under the free flow condition, driving speed can be adequately described by a normal distribution [34], [35]. This paper focuses channelization design

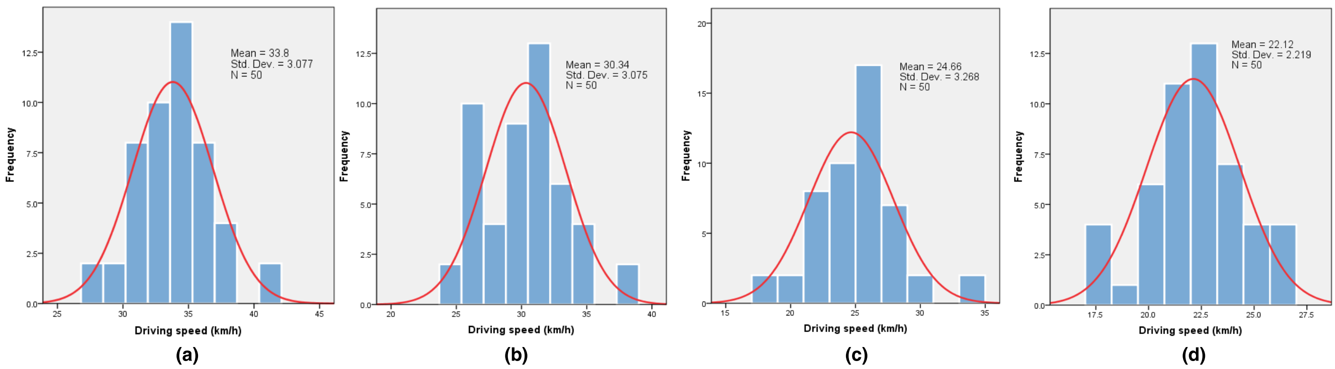


FIGURE 3. Driving speed distributions in four stages of channelization. (a) "appearance of channelization." (b) "beginning of channelization." (c) "middle of channelization." (d) "end of channelization."

TABLE 3. Distribution parameters and Kolmogorov-Smirnov test.

Stages	Normal distribution parameters		Sample sizes	K-S test
	μ	σ	N	Asymp. Sig. (2-tailed)
Appearance	33.80	3.08	50	0.497
Beginning	30.34	3.07	50	0.684
Middle	24.66	3.27	50	0.281
End	22.12	2.22	50	0.338

in general and only considers the free-flow vehicle conditions, so driving speed in four stages can be represented by normal distributions. Figure 3 demonstrates the distributions of driving speed when drivers pass through the four stages of channelization. Distribution parameters and the results of Kolmogorov-Smirnov (K-S) test are listed in Table 3. All these four distributions pass K-S test (Asymp.Sig. > 0.05), indicating that they are all nearly normally distributed. For this central channelization, driving speed in the "appearance of channelization" stage, "beginning of channelization" stage, "middle of channelization" stage and "end of channelization" stage approximately conforms to normal distributions N(33.80, 3.08^2), N(30.34, 3.07^2), N(24.66, 3.27^2) and N(22.12, 2.22^2), respectively. According to mean values of these four distributions, it can be observed that drivers decelerate when channelization appears in the visual field. When vehicles turn into the channelization, they are more likely to slow down Driving speed is slightly reduced when drivers try to merge out of the channel.

2) CALCULATION MODEL WITH BAYESIAN INFERENCE

Bayesian inference has been widely used in the transportation field, and some studies have defined the advantages of Bayesian inference over classical statistical methods [36]. The Bayesian approach differs from the classical likelihood-based theory since all unknown parameters are supposed to be random variables and these variables are defined by a prior distribution. This prior distribution is incorporated with the traditional likelihood to compute the posterior distribution of the parameter of interest on which the Bayesian inference is based [37]. The prior distribution represents the available information before any observed data are taken into consideration. In the Bayesian statistics, the prior beliefs of the unknowns are updated by the probability of observed data and the influence of the posterior inference. Sometimes, prior information cannot be obtained. In this case, non-informative or vague prior distributions with large variance need to be specified. That is to say, such prior information has a negligible effect on the posterior distribution. WinBUGS is a popular software to implement Bayesian inference. In this software, Markov chain Monte Carlo (MCMC) methods are used to generate samples from the posterior distribution.

The 95% Bayesian credible interval (95% BCI) can be used to identify the significance of covariates. If the zero value does not stay in the 95% BCI of the posterior distribution of a coefficient β, the corresponding explanatory variable X will have a significant contribution to the response variable Y. The relationship between the explanatory and response variables is indicated by the signs of the posterior summaries of central and relative locations (e.g., mean. median, 2.5%, and 97.5% percentile). If all of them are positive or negative, then there is strong evidence for the association. Moreover, if the value of Monte Carlo (MC) error is lower in comparison to its posterior standard error, the posterior density is estimated with accuracy. The precision of the model is given by the R_B^2 statistic, which can be calculated as follows:

$$R_B^2 = 1 - \frac{\sigma^2}{s_Y^2} \tag{3}$$

where σ^2 is the variance; s_Y^2 is the sample variance of Y.

The relationship between curvature and driving speed is close to the form of exponential function [38], while driving speed has a strong correlation with the logarithm of sight distance [39]. In the study, shape parameters of the drivers' visual lane model are regarded as explanatory variables. The response variable V (driving speed) is considered to be a continuous random variable defined in the whole set of real numbers following the normal distribution with mean μ and variance σ^2.

Then the distribution of driving speed can be summarized by the following equations:

$$V|vS_{12}, vS_{23}, vS_{34}, vK_{12}, vK_{23}, vK_{34} \sim N\left(\mu\left(\beta, vS_{12}, \ldots, vK_{34}\right), \sigma^2\right) \quad (4)$$

With

$$\mu\left(\beta, vS_{12}, \ldots, vK_{34}\right) = \beta_0 + \beta_1 \ln\left(vS_{12}\right) + \beta_2 \ln\left(vS_{23}\right) + \beta_3 \ln\left(vS_{34}\right) + \beta_4 e^{vK_{12}} + \beta_5 e^{vK_{23}} + \beta_6 e^{vK_{34}} \quad (5)$$

where $\beta = (\beta_0, \beta_1, \ldots, \beta_6)^{\mathrm{T}}$ are the set of regression parameters under estimation.

Normal distributions N (0, 1000) were considered as non-information priors for regression coefficients β. An inverse gamma distribution IG (0.01, 0.01) was assumed for the variance σ^2 as the vague prior distribution. For each model, a chain of 12,000 iterations was established in WinBUGS. The convergence of the chain was checked visually using trace and history plots, and examined by the Brooks, Gelman and Rubin convergence diagnostics [40]. After ensuring convergence, first 2,000 samples were discarded as adaptation and burn-in iterations. According to the 95% BCIs, insignificant variables were eliminated. Then we repeated the above steps, and the final models of driving speed distributions during the four channelization stages were calculated as shown in Table 4.

On the basis of posterior summaries in Table 4, the values of R_B^2 are 0.92, 0.91, 0.79 and 0.85 for these models, indicating that these models have relatively high precision. For all estimated parameters, Mc errors are lower than standard deviations (S.D.). This demonstrates that the posterior distributions of parameters are estimated with accuracy. In the light of the posterior summaries of central and relative locations (mean. median, 2.5% and 97.5% percentile), the association between the drivers' visual perception and driving speed can be illustrated. As to these four stages, the visual curve length has a positive correlation with driving speed, which means that as the visual curve length increases, drivers are more likely to increase their driving speed. On the contrary, the visual curve curvature is negatively correlated with driving speed, indicating that drivers tend to slow down with the growth of the visual curve curvature. In the "appearance of channelization" stage, all shape parameters of drivers' visual lane model in three characteristic regions affect driving speed significantly. In the "beginning of channelization" stage, shape parameters in the "near scene" are the only ones with indistinct effect on driving speed. In the "middle of channelization" stage, all parameters except the visual curve cumulative length in the "middle scene" vS_{12} have notable influences on driving speed. In the "end of channelization" stage, the "near scene" and "far scene" of the drivers' visual lane model have distinct impacts on driving speed.

TABLE 4. Posterior summaries for driving speed distributions.

Parameters	mean	Std	MC error	2.5%	median	97.5%
Appearance of Channelization						
R_B^2	0.92	0.03	0.0003	0.87	0.92	0.95
β_0	-16.88	2.869	0.04	-23.87	-17.15	-13.53
β_1	5.26	0.25	0.005	4.27	5.23	5.69
β_2	6.78	0.76	0.006	4.68	7.00	9.31
β_3	9.05	1.43	0.01	4.96	9.06	12.59
β_4	-18.82	4.88	0.09	-29.91	-18.36	-8.76
β_5	-25.22	3.75	0.08	-34.44	-25.63	-17.45
β_6	-17.26	3.87	0.09	-27.19	-17.81	-9.53
σ^2	4.02	0.64	0.007	2.67	4.12	5.37
Beginning of Channelization						
Parameters	mean	Std	MC error	2.5%	median	97.5%
R_B^2	0.91	0.03	0.0003	0.86	0.92	0.96
β_0	-7.78	2.85	0.02	-15.69	-7.96	-2.53
β_2	3.39	0.34	0.003	2.26	3.38	4.06
β_3	6.62	0.36	0.003	4.92	6.66	7.17
β_5	-8.98	4.09	0.09	-16.75	-8.78	-1.52
β_6	-9.90	4.05	0.07	-16.99	-10.50	-1.65
σ^2	4.86	0.58	0.006	3.02	4.46	5.61
Middle of channelization						
Parameters	mean	Std	MC error	2.5%	median	97.5%
R_B^2	0.79	0.10	0.001	0.60	0.79	0.86
β_0	-6.49	4.35	0.09	-18.51	-6.27	-0.06
β_1	6.38	0.41	0.004	4.77	6.35	7.06
β_3	1.83	0.32	0.003	0.96	1.81	2.43
β_4	-6.62	4.39	0.10	-21.06	-6.92	-0.13
β_5	-8.90	4.36	0.09	-19.76	-9.38	-1.82
β_6	-7.35	4.23	0.11	-18.73	-6.73	-0.33
σ^2	3.37	1.27	0.02	0.99	3.07	5.33
End of channelization						
Parameters	mean	Std	MC error	2.5%	median	97.5%
R_B^2	0.85	0.06	0.0007	0.74	0.86	0.90
β_0	-9.23	4.12	0.11	-19.06	-9.69	-2.52
β_1	6.31	0.41	0.004	5.17	6.34	7.42
β_3	1.79	0.32	0.003	1.08	1.83	2.23
β_4	-10.91	4.11	0.08	-20.06	-10.31	-3.51
β_6	-8.52	4.05	0.08	-18.87	-9.06	-2.35
σ^2	3.35	1.04	0.01	1.01	3.06	5.35

B. VISUAL INFORMATION FROM DIFFERENT VISUAL ANGLES WITH 3D MOBILE MAPPING

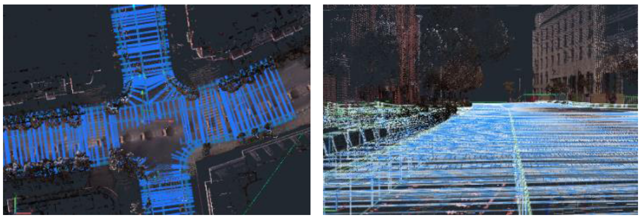
Visual angles vary from driver to driver at the same location. The same driver also has a number of angles for visual perception at different moments while driving in the same location. Three-dimensional mobile mapping experiments can take the place of a large number of repeated naturalistic driving experiments, since it is much easier to adjust observation points simulating various visual angles. Hence, this study applied 3D mobile mapping to acquire the information about possible drivers' visual perceptions.

First, point-cloud information was obtained by 3D mobile mapping as the basic information library of road environments. The longitude and latitude coordinates of original point cloud data were transformed into three-dimensional geographic information coordinates under the Beijing 1954/3-degree Gauss-Kruger CM 120E coordinate system. Then the classification and noise reduction of the point clouds were managed by Bentley Microstation, and key information

TABLE 5. Evaluation method of geometric design consistency on highways.

Difference between operating speed and design speed (for a specific road section)	Speed difference between adjacent road design elements	Rating
$\lvert V_{85} - V_{design} \rvert \leq 10\ km/h$	$\lvert \Delta V_{85} \rvert \leq 10\ km/h$	Good
$10\ km/h < \lvert V_{85} - V_{design} \rvert < 20\ km/h$	$10\ km/h < \lvert \Delta V_{85} \rvert < 20\ km/h$	Fair
$\lvert V_{85} - V_{design} \rvert \geq 20\ km/h$	$\lvert \Delta V_{85} \rvert \geq 20\ km/h$	Poor

was extracted separately including road alignment, surrounding environments, and so forth, as shown in Figure 4.



(a) (b)

FIGURE 4. The segmentation and classification of 3D point clouds. (a) segmentation by road function. (b) point clouds classification.

The conversion of data formats was handled by Autodesk Recap, and the observation point in the model was adjusted to the drivers' eye height. Natural horizontal and vertical rotation angles of drivers' head were 45° and 30° [41], so the observation angle could be adjusted according to the rotation range of drivers' vision. Drivers' visual lane models were established from different visual angles. Driving speed distribution in the four stages could be computed after shape parameters of drivers' visual lane models were substituted into the calculation models. Figure 5 shows several samples of drivers' visual lane models from different visual angles at the same "middle of channelization" stage in a central channelized island.

C. EVALUATION METHOD ON CHANNELIZATION

As mentioned in the Introduction, channelization has four main problems. The core of these problems is unreasonable vehicle speeds passing through channelization, resulting in low reliability and capacity. To take these issues into account, the study expressed internal elements of the driving process through channelization by four stages. Figure 6 illustrates the evaluation method on channelization. For highways, geometric design consistency can be evaluated by speed metrics as shown in Table 5 [42]. For channelization on urban roads, driving speed lower than on highways, so the criterion of speed difference was chosen as 10km/h (for specific stages of channelization) and 20% (between adjacent stages).

In Figure 6, A, B, C and D denote the "appearance of channelization," "beginning of channelization," "middle of channelization" and "end of channelization" stages, respectively. In the "beginning of channelization," driving speed should be in a reasonable range around the roadway design speed. The design speed is denoted by V_{d1}, and the upper and lower limits for the reasonable range of entering the channelization are specified as $V_{d1} + 10$ km/h and $V_{d1} - 10$km/h. In the "end of channelization" stage, the speed difference between vehicles and their target traffic flow should be reduced, so the merging speed is controlled to a range from $V_{d2} - 10$ km/h to $V_{d2} + 10$ km/h, where V_{d2} denotes the design speed of the through lane. If there exists a considerable gap between design speeds of the two intersecting roads, an acceleration or deceleration lane is needed. In this situation, V_{d1} or V_{d2} is defined as the design speed of the corresponding acceleration or deceleration lane.

If channelization has poor recognizability, drivers are more likely to reduce their speed sharply before they enter the channelization. Hence, the decrease of driving speed needs to be less than 20% from the "appearance of channelization" stage to the "beginning of channelization" stage, as shown in the orange area of Figure 6. When vehicles fully enter channelization, insufficient sight distance will lead to poor speed continuity. To ensure a smooth driving process, as shown in the green area of Figure 6, from the "beginning of channelization" stage to the "middle of channelization" stage, the reduction of driving speed needs to be less than 20%. The blue area demonstrates that the increase of driving speed from the "middle of channelization" to the "end of channelization" stage should not be more than 20%. Driving speed distributions that fall within the three acceptable areas means that the channelization is well designed with high safety and efficiency, as shown in Figure 6.

D. CASE STUDY

A right-turn channelized island in the intersection of Bai'an Road and East Changji Road was chosen as a case study, where roadway design speed is 30km/h. The evaluation process is as follows:

(1) Information in the four stages from different visual angles is obtained by 3D mobile mapping. Drivers' visual lane models are established based on point clouds, and corresponding shape parameters are extracted. Totally, 100 valid samples are collected. Figure 7 demonstrates an example of drivers' visual lane models in four stages from one visual angle.

(2) Driving speed distributions in four stages are calculated based on Table 4. The results show that driving speed in the "appearance of channelization," "beginning of channelization," "middle of channelization" and "end of channelization" stages approximately obey normal distributions N $(34.90, 2.87^2)$, N $(32.59, 3.01^2)$, N $(26.10, 3.48^2)$ and N $(21.31, 2.28^2)$ respectively.

(3) The ranges of driving speed in four channelization stages are defined as $[\mu - 2\sigma, \mu + 2\sigma]$, where μ and σ are the mean value and standard deviation of a normal distribution. The result is represented by the blue area in Figure 8. The acceptable range of driving speed is denoted by the green area in Figure 8. The area filled with diagonal lines, outside of the green corridor signifies that actual driving speed fall outside

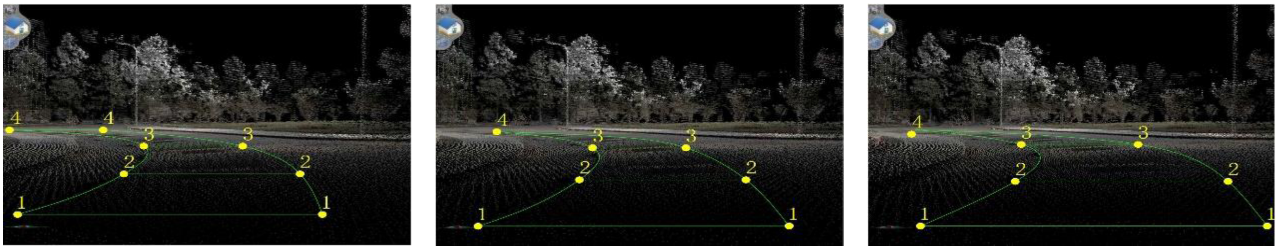


FIGURE 5. An example of drivers' visual lane models from different visual angles at the same "middle of channelization" stage.

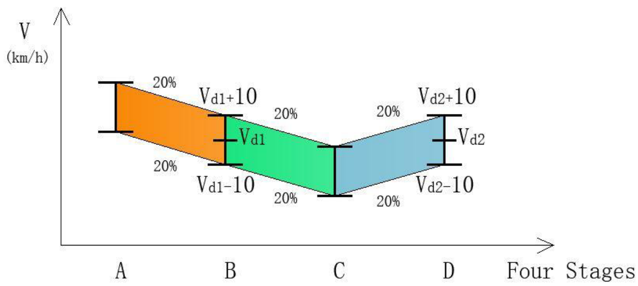


FIGURE 6. Evaluation method on channelization.

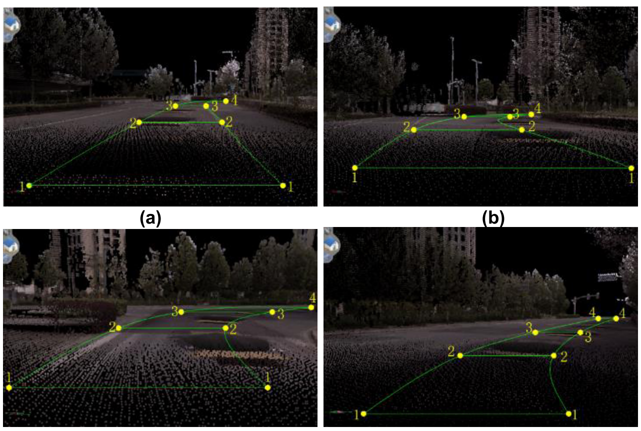


FIGURE 7. Different visual angles in four stages with 3D mobile mapping. (a) "appearance of channelization". (b) "beginning of channelization". (c) "middle of channelization". (d) "end of channelization".

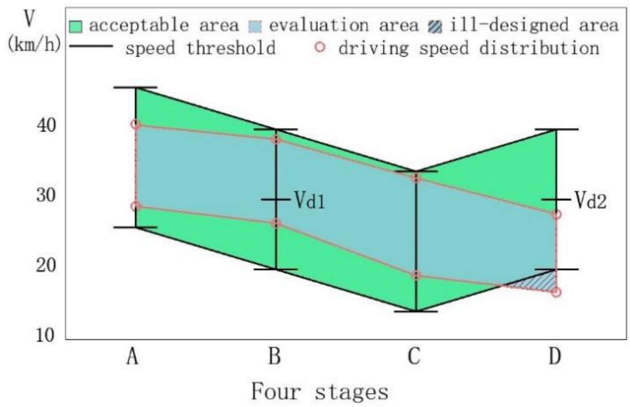


FIGURE 8. Evaluation result for the right-turn island.

the recommended ranges and suggests that these stages are ill-designed and need to be modified.

For this right-turn channelization, Figure 8 shows that driving speed in the "end of channelization" is less than the lower limit. According to Table 4, shape parameters of drivers' visual lane models that have significant impacts on driving speed of the corresponding stage can be adjusted to increase driving speed. When vehicles leave the channelization, shape parameters in "near scene" and "far scene" are closely linked with driving speed. Hence, driving speed in the "end of channelization" can be controlled by increasing visual curve length (vS_{12}, vS_{34}) and decreasing visual curve curvature (vK_{12}, vK_{34}).

V. DISCUSSION AND CONCLUSION

This study used 3D mobile mapping to explore an evaluation method of intersection design through drivers' visual perception. The evaluation method was based on the idea that proper intersection design needs to produce appropriate driving speeds, which can ensure road safety and efficiency. More than 30% of the total intersection-related crashes can be reduced by using well-designed channelization [25], [43]. The driving process through channelization consists of four stages: "appearance of channelization," "beginning of channelization," "middle of channelization," and "end of channelization." Unlike previous studies, this evaluation method addresses the four main problems for channelization, since the four channelization stages align with these problems.

These four problems have already been presented in previous studies, but there still are not any current evaluation methods for intersection design that can take all these issues into account. Small channelized right-turn islands may be ignored, so curbed corner islands should be at least 50 ft^2 at urban intersections and ideally as large as 100 ft^2. Low entry angles on channelization made drivers disregard the give-way line and generate high entry speeds [9]. Excessive entry and exit radii of channelization resulted in high entry, circulation, and exiting speeds [44]. Inadequate deflection on channelization brought about high entry speeds, leading to more rear-end crashes and angle crashes [10]. Insufficient sight distance was related to approximate 10% crashes on channelization [8]. Autey *et al.* [11] found that conventional channelization had significantly more merging and rear-end conflicts than modified channelized islands.

Drivers' visual lane models were established based on the Catmull-Rom spline, to quantify the road information from drivers' visual perception. In different stages of channelization, three characteristic regions ("near scene," "middle scene" and "far scene") have different impacts on driving speed. Driving speed distributions in the four stages obey normal distributions. Shape parameters of the driver's visual lane model were chosen as explanatory variables to calculate speed distributions by Bayesian inference. Three-dimensional mobile mapping was shown to be a good substitute for extensive naturalistic driving experiments to obtain drivers' visual perception from all possible visual angles.

Compared with previous studies, the evaluation method in this paper puts more focus on the inner structure of channelization design while taking into consideration drivers' visual perception and driving behavior. This evaluation approach helps road designers to identify which part of channelization features needs to be improved, and then provides modification suggestions. Besides, findings in this study also can contribute to the improvement of automated driving technologies, since 3D point clouds information can provide more comprehensive and precise road information for automated vehicles and help them make timely and accurate decisions. Driver trust in automated vehicles also can be improved, since the visual lane model enables automated driving vehicles to understand road design from the perspective of drivers and then control vehicles more consistently with drivers' expectations of driving safety and comfort. One of the limitations in this study is that more naturalistic driving samples passing through channelization need to be supplemented. In the future, more sources of road information will be included, such as traffic flow, traffic lights, and a more elaborate and comprehensive drivers' visual lane model will be developed. In this way, road design could better satisfy drivers' demands, making road traffic safer and more efficient.

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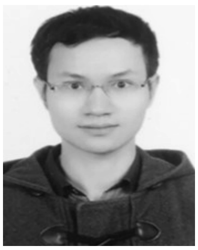

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