



Middle-aged Drivers' subjective categorization for combined alignments on mountainous freeways and their speed choices



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ABSTRACT

Road geometric design is a fundamental factor that impacts driving speed. Previous research generally paid attentions to the influences of specific road characteristics (e.g. curvature) on driving behaviors. Limited studies have focused on how drivers identify different alignments and how they further take the varying speed choices. This study aims at filling the gap by investigating the subjective categorization of road alignments based on middle-aged driver groups. A total of sixteen participants with ages ranging from 23 to 40 years were recruited. Participants were first asked to undertake naturalistic driving tests on a four-lane divided mountainous freeway while photos of the road and the driving speed were collected. Participants were then asked to subjectively sort the photos of the road into piles, within each pile we considered their driving behaviors would be similar. Finally, questionnaire survey was conducted in terms of comfort, safety, speed choice and sight distance. The picture grouping revealed three distinct and non-overlapping subjective categories of road alignment. And driver's ratings about comfort and safety were significantly different between these categories. The category with the largest sight distance and highest speed choice turned out to have the lowest rating in comfort and safety (note that the rating scales for comfort and safety had reversed polarity such that low numbers indicated high comfort and high safety). Statistical evidences indicated that the drivers have developed underlying mental schema about road alignment. Therefore, their speed choices on combined alignment were further investigated. The difference between actual driving speed and driver's expected speed showed close relation to the ratings and significant difference between two of the categories. Road with large absolute value in speed difference informed inconsistency between geometric design and driver's expectation from the aspects of drivers' perception and expectation of the road. The findings provided insight into how middle-aged driver views and categorizes road alignment. And it was found that the drivers relied on visual characteristics of the alignment to distinguish the categories instead of separate horizontal and vertical geometric parameters. It was implied that more considerations should be taken into driver's perception of road during alignment design to improve road safety.

1. Introduction

The literatures have suggested that the geometry of road layouts have major influence on driver's behavior. Tons of studies have investigated the effects of specific road geometric design on driving performances, including speed, lane departure, crashes, and etc. (Montella et al., 2014; Mclean, 1981; Eustace et al., 2014; Banihashemi, 2016; Gargoum and El-Basyouny, 2016; Yu et al., 2018b). These studies mainly focus on separate horizontal and vertical road alignment to explore the influence of geometric design on driving behavior. However, road is a complete three-dimensional geometry and analyzing it

from the two-dimensional aspect would cause limitations, especially in mountainous areas where both horizontal and vertical curves vary substantially. In addition, previous researches mainly paid attentions to geometric features at a certain location or of a small road segment, which ignored the whole section of road from driver's point of view.

Road geometry affects drivers' perceptions of driving environment and therefore further influences the driving behaviors (Janssen et al., 2006). Driver's perception and expectation for the road and road environment were used to explore driver's desired speed and the setting of creditable speed limit (Aarts et al., 2009; Gargoum et al., 2016). Goldenbeld and van Schagen, (2007) explored speed limit credibility on

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80 km/h speed limit rural roads and showed that the degree of credibility was related to a number of characteristics of the road and the road environment, such as the presence or absence of a curve and characteristics concerning the field of view (sight distance, clarity of situation).

To further explore how drivers view and describe road alignment, this study analyzed middle-aged driver's perception of road to determine subjective road categorization. Since drivers' self-developed mental schema of road types would lead to their expectancies of the road in order to guide a safe and comfortable journey (Bellet et al., 2009). It's critical to determine whether drivers would form categorizations about roads that reflect their mental schema for familiar roads based on the features of alignments.

Road categorization studies have been employed to reveal driver's mental schematic structure of road. And several studies have been conducted to determine how the drivers distinguish the urban/rural roads with a combination of features such as lane width, presence of marked center line, curves, intersections, carriageway (Stelling-Konczak et al., 2011; Kaptein and Claessens, 1998). Charlton and Starkey, 2017a found that participants readily discriminated between different types of rural road based on curves, intersections, lane separation and road width. These categories correctly predicted significant difference in participants' explicit judgement about speed, difficulty, physical comfort, and safety of road. How road schema is organized and what elements of the road environment it contains are key to understanding how the drivers are able to observe the roads and make decisions of vehicle operations (Amedeo and York, 1990). Analyzing the drivers' categorization about road considering single geometric features of combined alignment would help engineers better understand driver's perception and expectation about road geometry in order to design road alignment with consistently safer and more enjoyable road user experiences (Charlton et al., 2010).

In the previous studies, drivers were asked to make judgements of static photographs to collect the speed choice data. Since speed decision based on still images is different from speed decision while driving, Charlton and Starkey, (2017a, b) applied a new experimental method to collect speed choice by having participants drive video images of urban road in a driving simulator. In this study, naturalistic driving was used to accurately acquire the driving speeds on road with still images used to learn about the drivers' expected speed choice. Besides, similar as several of the previous road categorization studies, the drivers were asked to sort photos of road scenes into different piles and rate specific attributes of each road.

Furthermore, in this study, the targeted driver group was middle age drivers. The objectives of this study are as follows: (1) to determine driver's subjective categorization for familiar roads based on the features of combined alignments, (2) to learn about driver's speed choice regarding the subjective categories. To achieve these above-mentioned goals, naturalistic driving on combined alignments was conducted to capture road scenes perceived by drivers and collect their on-road driving speed. Road features aside from geometry were kept consistent

to avoid other factors' impact on speed choice. Following which, the drivers were asked to sort photos of the road scenes into different, behaviorally similar piles. The same photos were then rated by drivers subjectively in terms of comfort, safety, expected speed and available sight distance. The differences between subjective classified categories were investigated. Aside from this, drivers' actual driving speed were compared to their self-reported speed choices to reveal the difference between their actual performances and expectations on different road alignments.

2. Experiment design and data acquisition

2.1. Participants

Middle-aged participants were chosen randomly through an open invitation (via posters and social media) where each received a gift of \$20 in thanks for involvement. It was made clear in the invitation that participants must meet certain criteria to join the experiment. To exclude driver factors such as age and driving experience, drivers younger than 20 and older than 45 were not included. Finally, 16 drivers were chosen to participate in the research, including 7 females and 9 males with their ages ranged from 23 to 40 years old ($M = 31.5$, $SD = 5.57$). All participants held valid driver's licenses and reported average licensed years of 11.44 years ($SD = 5.48$, range 3–19). The reported average driving distance over 3000 km per year. None of them had any record of mental illness or unhealthy physical conditions such as frequent headache or heart diseases. Participants were informed of the process of this experiment and they all reported willingness to complete both the real vehicle driving task and the image assessment.

2.2. Experiment road select

A 30 km four-lane divided mountainous freeway in Zhejiang Province, China, was chosen to ensure a wide range of vertical and horizontal geometric characteristics. The road consisted of 44 horizontal curves with maximum curvature of 2.5 km^{-1} and minimum curvature of 0 km^{-1} . The longitudinal grades varied from -5.0% to $+5.0\%$. The standard cross-section was 24.5 m width with 3.75 m lane width and 2.5 m shoulder width. A total of 40 location/road scenes with combined horizontal and vertical alignments were chosen. The scenes were selected with varied curvatures and at different location of curves. Both left turn curves and right turn curves were included. The tested location/road scenes were at least 100 m away from ramps, bridges and tunnels. Summary statistics of the geometric features of the chosen scenes were shown in Table 1.

In mountainous freeway, the sight distance a driver can perceive at certain location is limited, especially at curves and slopes. In general, available sight distance is compared to stopping sight distance in order to ensure safe and efficient operation of a roadway (Gargoum et al., 2018). Factors affecting the length of sight distance include road 3D geometry, driver's position and vision. Since available sight distance in

Table 1
Geometric characteristics of the analyzed road scenes.

Curvature (km ⁻¹)	road scene number	Gradient (%)	road scene number	Sight distance (m)	road scene number
< = 0.5	s9 s16 s36 s37 s40 s14 s25 s27 s31 s28 s39	< = -0.3	s3 s4 s5 s17 s18 s19	< = 140	s2 s5 s11 s12 s17 s32 s39
> 0.5& < = 1.0	s1 s6 s17 s21 s22 s24 s30 s38	> -0.3& < = -1.0	s1 s2 s6 s7 s8 s9 s20 s21	> 140& < = 160	s1 s4 s7 s8 s14 s15 s16 s20 s30 s33 s34 s38
> 1.0& < = 1.5	s13 s26 s29 s32 s33 s34 s35	> -1.0& < = 1.0	s13 s22 s23 s28 s31 s34 s35 s36	> 160& < = 180	s18 s19 s23 s26
> 1.5& < = 2.0	s4 s10 s15 s18 s19 s20 s23	> 1.0& < = 3.0	s10 s12 s24 s25 s26 s27 s29 s33 s39 s40	> 180& < = 200	s10 s22 s25 s35
> 2.0& < = 2.5	s2 s3 s5 s7 s8 s11 s12	> = 3.0	s11 s14 s15 s16 s30 s32 s37 s38	> 200	s3 s6 s9 s13 s21 s24 s27 s28 s29 s31 s36 s37 s40



Fig. 1. Sight distance from the driver's vision view in point clouds (left) and corresponding road scene (right).

a way depicts three-dimensional geometric characteristics of alignment considering driver's perception, it was calculated at each tested road scene using point cloud data collected by laser scanning technology. The lidar data was obtained before this experiment and it enabled the researchers to evaluate the sight distance from the exact perspective of driver's view (Fig. 1). The summary statistics of the sight distances of the test scenes were also shown in Table 1.

2.3. Naturalistic driving test

To collect the drivers' actual behavior in the 40 road scenes, naturalistic driving tests were carried out during daytime, in good weather condition and with limited traffic flow. During the tests, the drivers were asked to try to keep on the left side of the road to reduce the variance of perception that participants had at each test location. Finally, all the participants were recorded to be on the same side of lane in each road scene. Tachograph (GARMIN GDR35) was used in this research and attached to the front windshield behind the rear vision mirror to appropriately record the road from driver's point of view. Driving position, velocity, three-axis acceleration and high-definition video (30 Hz frame rate) were recorded synchronously, which were stored as AVI files. The recorder can avoid GPS signal interference to camera lens and match GPS with driving video information accurately. The GPS data attached to video frames helped match image data with lidar data, therefore it facilitated road geometry extraction in lidar dataset for the tested road scenes.

2.4. Picture sorting and road rating

For each participant, a total of 40 color photos of the corresponding test locations were taken using high definition video recorders. The photos used in the current study were selected with the purpose of depicting a representative range of roadway geometry from driver's point of view. For the picture sort task, the color photos were printed individually on A5 paper (210 mm wide × 148 mm). And the participants were provided with photos in a random order and were asked to group them into three and above piles according to their own judgement of road geometric similarity. Meanwhile, they could make as many piles as they wanted so that their driving performance would be the same for all road scenes in one pile and different to the road scenes in other piles. The number of times each image was sorted with each other was calculated for the group as a whole.

For the rating task, the photos and four questions underneath were printed in a A5 booklet (Fig. 2). The first question is for rating the comfort with a scale of 1–3. The second question asked the participants to rate how safe they would feel if they were driving the road on a scale of 1–5. The next question asked what speed they would choose on the road (expected speed choice) and the final question asked the participants about the estimation of sight distance.

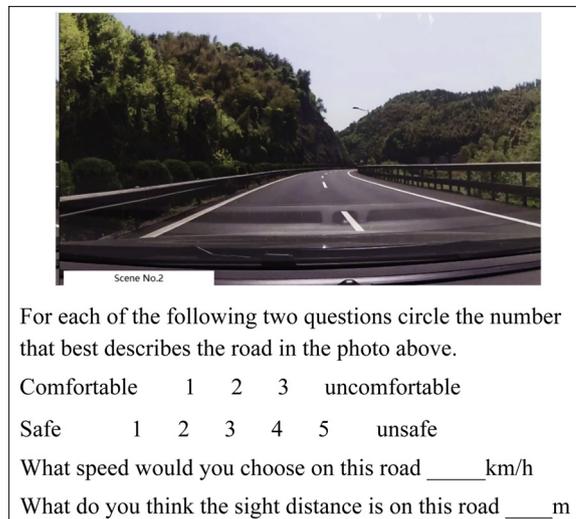


Fig. 2. Layout of the booklet in picture rating task.

2.5. Procedure

Three tasks consisted of the experimental sessions: naturalistic driving, picture sort and rate. Participants were recruited on dry weather day to drive at the same direction, from Xinchang county to Baihe county, on G15 freeway. The typical driving task took 25 min to complete. Then, given a 30 min' rest time period, they were provided the picture sort task, which they were given the 40 images extracted from their individual tachograph videos in a random order and asked to sort them into piles. After finishing picture sorting, the participants were given road rating booklet which contained rating questions for each of the 40 images also in a random order. The typical picture sort and rate task took 20 min. The tests of picture sort and rate were arranged right after the naturalistic driving to ensure that participants could judge the road images based on what they had just driven.

3. Analysis result

3.1. Subjective categorization

In order to identify middle-aged participant's subjective categorization of combined alignments, the number of times each photo was sorted in a group with another was processed as a 40 × 40 similarity matrix, which was used to calculate a multidimensional scaling (MSD) solution (normalized raw stress = 0.143, RSQ = 0.881). As shown in Fig. 3, the physical positions of the 40 road photos were mapped into two-dimensional space based on the frequency they were sorted together by participants. The closer the two photos were, the more times they were grouped together during picture sorting. Furthermore, the same similarity matrix was used in hierarchical clustering analysis to

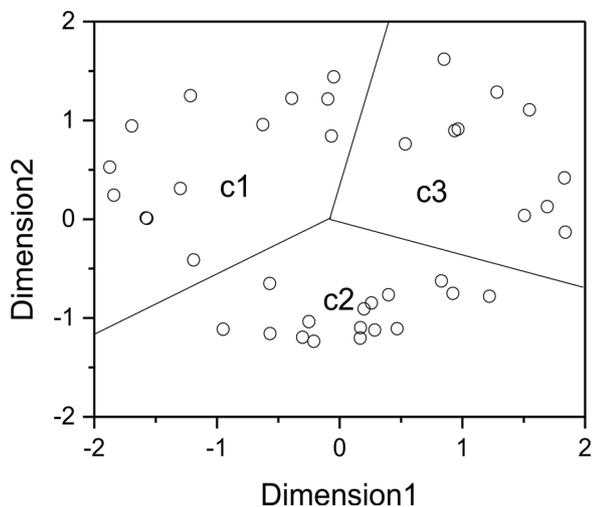


Fig. 3. Multidimensional scaling solution for participants' picture sort of 40 combined alignment scenes. Superimposed is the result of a hierarchical cluster analysis of the same similarity matrix that produced a non-overlapping three-cluster solution.

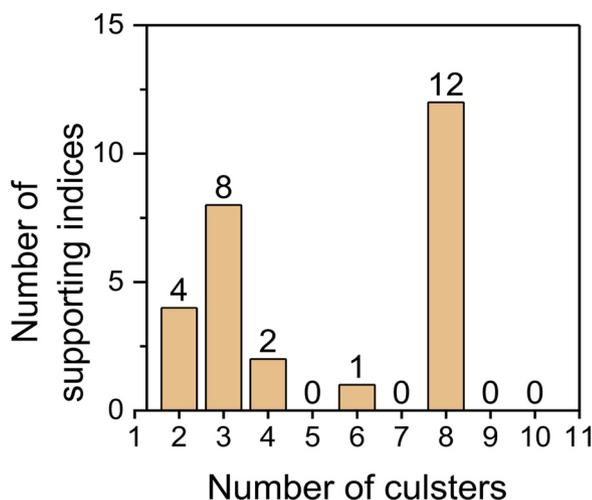


Fig. 4. Supporting indices for cluster number (1–11) calculated in NbClust package (in R).

figure out the boundaries of the photos. NbClust package (in R) was applied to determine the number of clusters in the dataset by counting the votes of thirty indices which measured the center and distance between clusters. As shown in Fig. 4, eight clusters had the maximum number of supporting indices of twelve and three clusters held the second maximum number of supporting indices of eight. Finally, three clusters were chosen for two main reasons. From one hand, previous research has shown that road users had limited distinguishing capabilities for road categories and six was the maximum number of categories they could handle (Kosztolanyi-Ivan et al., 2016). Another issue is that during experiment, participants subjectively sorted the photos into an average number of 3.81 piles with the max piles of 5. Three clusters were more consistent with the real situation. Finally, three non-overlapping road categories were shown in Fig. 3.

For each picture, mean rating of comfort, safety, self-reported speed choice and estimated sight distance were calculated. The ratings of the three categories were plot using boxplot and the mean values were plot in the shape of a circle as shown in Fig. 5. One-way MANOVA analysis showed that the ratings had significant difference between the three categories (Wilks' Lambda = 0.005; $p < 0.05$, $\eta_p^2 = 0.995$). Least-Significant Difference (LSD) test indicated that the ratings of comfort and

safety were significantly different between every two of the three categories ($p < 0.05$). Ranking of both the mean comfort and mean safety for the three categories came as: $c1 < c2 < c3$ (Note that the rating scales for comfort and safety had reversed polarity such that low numbers indicated high comfort and high safety). Judgment of speed choice in $c3$ ($M = 77.08$, $SD = 13.04$) was significantly lower than that in $c1$ ($M = 90.72$, $SD = 13.00$, $p < 0.05$) and $c2$ ($M = 86.18$, $SD = 8.41$, $p < 0.05$), while $c1$ and $c2$ didn't show significant difference between each other in expected speed ($p = 0.292 > 0.05$). As for estimated sight distance, road in $c1$ had ($M = 265.24$, $SD = 115.32$) significantly larger value than that in $c2$ ($M = 170.76$, $SD = 39.08$, $p < 0.05$) and $c3$ ($M = 161.20$, $SD = 31.57$, $p < 0.05$), but significant difference wasn't shown between $c2$ and $c3$ ($p = 0.837 > 0.05$). Therefore, visual road alignments in $c1$ were those that provided good comfort, high safety and long sight distance as well as high speed expectation. Road scenes in $c2$ were featured with relatively short sight distance but still ensured fairly good ratings in comfort and safety. Drivers had high speed expectation in $c2$. Road scenes in $c3$ were also with short sight distance but had the least comfort and safety. Low expected speed choice was shown in $c3$.

Expected speed choice showed positive correlation with estimated sight distance ($r = 0.554$, $p < 0.01$) and negative correlation with comfort rating ($r = -0.672$, $p < 0.01$) and safety rating ($r = -0.635$, $p < 0.01$). It makes sense that the more discomfort and risky driver feels about the road alignment, the lower speed they would choose to diminish the danger. Moreover, both comfort and safety ratings had negative correlations with estimated sight distance ($r = -0.603$, $p < 0.01$; $r = -0.627$, $p < 0.01$), which meat middle-aged participants' rating about roadway had something to do with how far they could perceive the road. Interestingly, comfort or safety had no such significant correlation with the two-dimensional alignment parameters at vehicle location (curvature and gradient).

3.2. Actual and expected speed

In addition, it is critical to determine how well the participants' judgement of sight distance matched with the sight distance measured in point cloud data and reveal the relationships between participants' self-reported speed choice and the observed speed during naturalistic driving study. Fig. 6 shows a strong positive correlation between the estimated sight distance and the measured sight distance ($p < 0.001$, $R^2 = 0.915$), which demonstrated the validity of this picture rating test. However, there was relatively weak correlations between expected speed choice and on-road speed ($p < 0.001$, $R^2 = 0.471$) as shown in Fig. 7. The linear regression model indicated that at lower speed (less than 90 km/h), participants' typical driving speed exceeded judgement of speed choice, while at higher speeds, the on-road speed tended to be lower than expected speed. Unlike self-reported speed choice, driving speed only showed significant correlation with comfort rating ($p < 0.01$, $r = -0.328$).

The difference between observed speed in driving situation and self-reported speed choice in picture rating (observed speed - self-reported speed choice) indicated inconsistency between driver's actual performance and the expectation on combined alignments. As shown in Fig. 8, a value of zero indicated a good match between driver's on-road speed and expected speed, a positive value occurred when the driving speed exceeded the expected speed choice, a negative value showed when the observed on-road speed was lower than the self-reported speed. The speed difference didn't show significant difference between the three categories ($p = 0.066 > 0.05$), but LSD test showed significant difference existed between $c1$ and $c3$ ($p < 0.05$) as well as between $c2$ and $c3$ ($p < 0.05$). Spearman's correlation solution revealed that the speed difference had positive correlation with comfort rating ($p < 0.01$, $r = 0.570$) and safety rating ($p < 0.01$, $r = 0.651$) and negative correlation with sight distance ($p < 0.01$, $r = -0.622$).

In cases where the speed difference was higher than 5 km/h (e.g.,

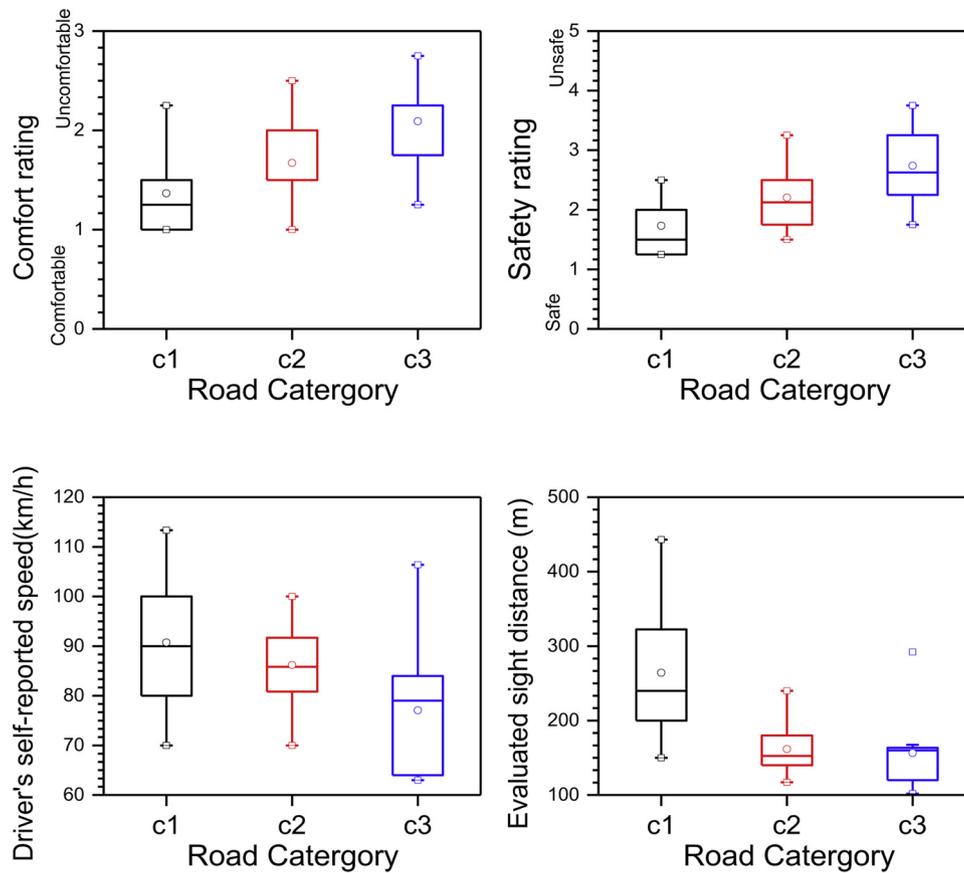


Fig. 5. Comfort, safety, self-reported speed choice and estimated sight distance for three road categories. Note that the rating scales for comfort and safety had reversed polarity such that low numbers indicated high comfort and high safety.

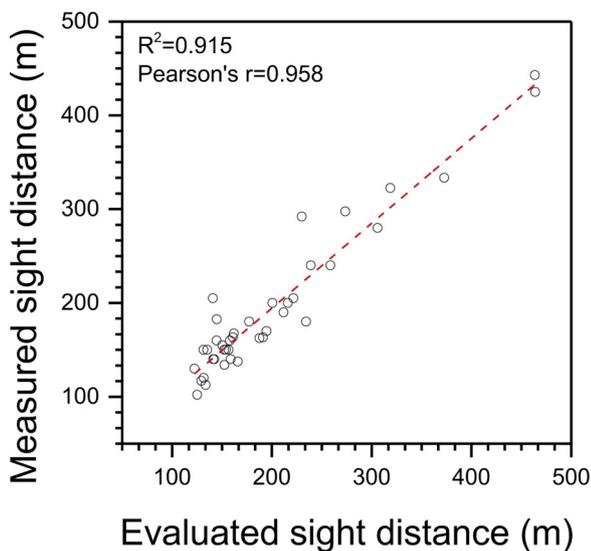


Fig. 6. Association between participants' estimation of sight distance and sight distance measured in point cloud dataset.

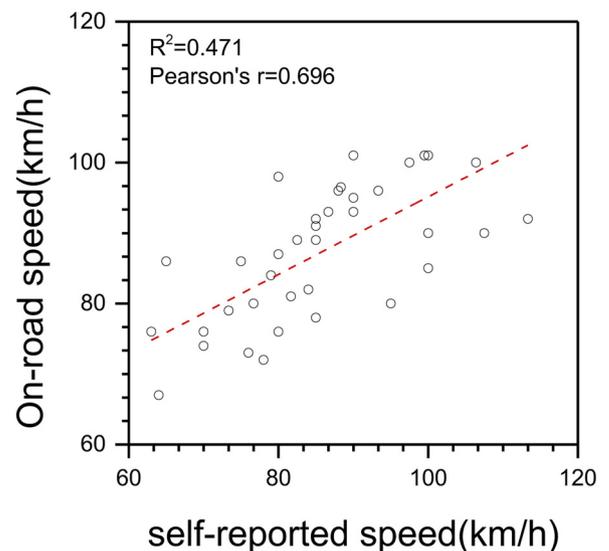


Fig. 7. Association between self-reported speed choice and observed on-road speed.

s5, s6, s12, s19, s29) or lower than -5 km/h (e.g., s16, s24, s32, s37), poor homogeneity was shown between driver's expectation and the actual driving performance, with s5 producing the maximum speed difference and s40 providing the minimum speed difference. For road showed poor homogeneity and negative value of speed difference, we found that more severe curves or slopes occurred before the tested road scenes. Where driving speed was lower than the self-reported speed choice, there was a speed "waste" which meant the provision of road

facilities did not match up with driver's expectation. For road showed poor homogeneity and positive value of speed difference, the rating levels of comfort and safety showed relatively high values (comfort: $M = 2.19$, $SD = 0.52$; safe: $M = 3.25$, $SD = 0.36$). Even though participants rated relatively low speed in those discomfort and unsafe road scenes and the driving speed was lower than the average on-road speed level, the observed speed still exceeded the judgement of speed choice and caused inhomogeneity. In that way, drivers tended to drive faster

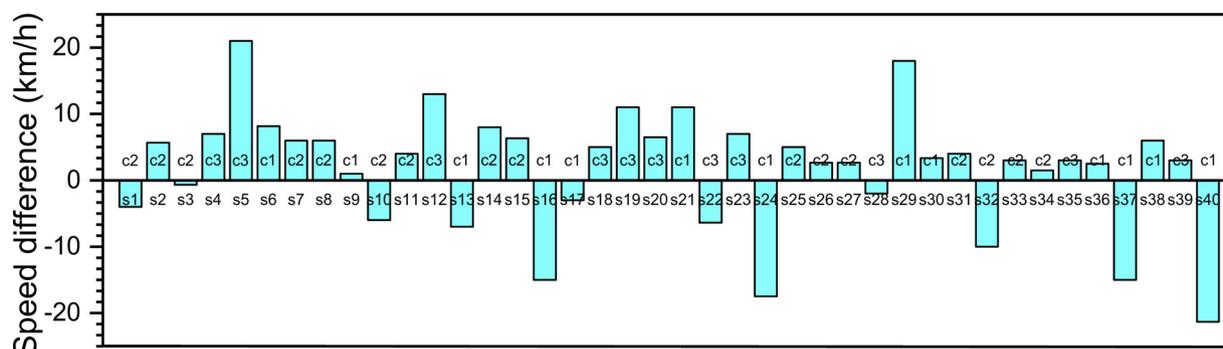


Fig. 8. Speed difference (observed speed – self-reported speed) of the 40 road scenes.

than the safe speed they thought the road provided. Accident records revealed that thirty crashes occurred at s5 and s29 from 2007 to 2011, among which twenty-four were reported to involve speeding. Alignment design in those sections should be paid extra attention to ensure that the geometric features of current and adjacent road don't violate driver's expectation to drive.

4. Discussions

This study distinct from the previous road categorization studies. We focused on middle-aged driver's mental schema of road geometric characteristics. After statistical analysis of the picture sort and rate about 40 road scenes with combined horizontal and vertical alignment, we found that this particular group of drivers did form distinct road categorizations considering alignment features. The picture sort and rate tests were conducted 30 min after naturalistic driving to ensure participants' familiarity with the road scenes. Three non-overlapping categories were identified, which showed significant difference in the participants' ratings about comfort, safety, expected speed choice and estimated sight distance. Moreover, the ratings of comfort and safety showed strong correlation with the self-reported speed choice. The strong correlation between driver's estimation of sight distance and the sight distance measured in point cloud dataset further proved the validity of the rating experiment. Therefore, there were solid evidence that middle-aged drivers had mental schema of different road alignments, the schema based on their prior driving experiences.

Furthermore, in the study, we used curvature, gradient and sight distance to represent the geometric features of road alignment. The first two were two-dimensional descriptive parameters. The third one was a three-dimensional parameter measured from driver's point of view. There was no significant correlation between picture rating and curvature or gradient. However, the ratings of comfort, safety and self-reported speed choice showed significant correlation with sight distance. Subjective categorization was more often based on the three-dimensional alignment from driver's vision view (sight distance) rather than the single horizontal or vertical parameter at vehicle location. In other words, driver's mental categorization of roadway had little to do with separate curvature and gradient at certain location but was affected by the three-dimensional geometric features taken from driver's point of view. Whereas, curvature and gradient were what designers generally referred to when designing road geometry. It is important to take driver's perception of roadway into consideration in design so that geometric features of road would meet driver's perception and expectation of road alignment. In the current study, we found that sight distance extracted from driver's point of view was a very effective parameter to represent driver's perception of road design. The type of demand on driver performance differ when road geometry in diver's view differs (Fuller, 2005). Advanced researches also focused on the lane characteristics from driver's vision view by building a visual lane model and studied the influence of visual lane on driver's speed and

lane keeping behavior (Yu et al., 2016, 2018a).

Besides, in comparison to the previous research where self-reported speed choice was used to represent driver's actual driving speed (Charlton and Starkey, 2017a; Weller et al., 2008), the speed choice during picture rating in the present experiment was implied as the expectation of speed. Driver's actual speed was collected through naturalistic driving which helped to acquire more accurate driving performance on the tested road scenes. When comparing participants' driving speed with self-reported speed on the mountainous freeway, the weak correlation was found. The difference between actual speed and expected speed were further calculated and analyzed, which presented significant correlations with comfort, safety and sight distance. Advanced research suggested that driver's speed on the combined alignment was not only influenced by the current road geometry but also affected by the adjacent road (Cafiso and Cerni, 2011). The speed difference may due to the continuously varied geometric features of mountainous freeway. Driver's behavior was constantly affected by the road geometry; therefore, the current driving performance was somewhat influenced by adjacent road. Samples showed inhomogeneity between the expectation of road and the actual driving behavior indicated that road geometric design fail to meet driver's expectation and violate driver's desired manner to control the vehicle.

5. Conclusion

This study was conducted to determine the middle-aged driver's subjective categorization of alignment in order to understand driver's perception and expectation of road geometric characteristics. The varying Road features for the combined horizontal and vertical alignments were included. The participants were asked to sort them into distinct and non-overlapping categories, which showed significant difference in their judgement about comfort, safety, expected speed choice and estimated sight distance. The revealed statistical evidences implied that the middle-aged drivers did develop underlying mental schema about different road alignments. These categories were based on the participants' experiences on the road and implied their expectancies and choices of driving behavior. It was found that drivers relied on visual characteristics of the road alignment to distinguish subjective categories instead of the separate horizontal and vertical geometric parameters usually used by designers. In this study, sight distance was measured in laser scanned point cloud dataset considering driver's view. Sight distance was closely associated with driver's ratings of comfort and safety as well as self-reported speed choice.

Besides, the participants' actual driving speeds had substantial differences with the subjective speed choices from picture rating in the mountainous freeway. And the differences between driving speeds and expected speeds were related with the ratings of comfort, safety and sight distance. When driving speed differed greatly from self-reported speed, either too low or too high, driver's expectation on the road was difficult to meet. The geometric design of the current road section did

not ensure homogeneity with the adjacent section to support consistent driving performance. The implication for this phenomenon is that driver's perception of roadway should be taken into consideration when designing combined alignment so that the geometry does not violate a motorist's expectation to drive and driver could control the vehicle in a safe manner.

Findings from the present study have contributed to the knowledge regarding road alignment categorization for the middle-aged drivers. For future study, one key issue is to recruit more participants with different categories of age and driving experience to study driver's perception and expectation about combined alignments.

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