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ORIGINAL PAPER

Vehicle trajectory at curved sections of two-lane mountain roads: a field study under natural driving conditions

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Abstract

Purpose The trajectory of a vehicle is comprehensively affected by the interactions between the vehicle, the driving behavior, and the road environment. High-risk driving behaviors and accident-prone road sections can be identified based on the relationship between the trajectory and road geometry. Previous related studies mostly focused on the trajectory deviation at a few points on the road, which cannot capture the continuous variation of the trajectory in an entire curve, and seldom considered the trajectory characteristics along curves with large deflection angles. The aim of this study is to investigate the trajectories passenger cars take on two-lane mountain roads and thus to determine the track patterns and its relevant risks.

Methods Field driving experiments were performed on four two-lane mountain highways, and vehicle trajectories under natural driving conditions were acquired. The continuous change in the lateral deviation rate of the trajectory was also determined by putting the measured trajectories into the coordinate frame together with the edge line of roadway. Further, the morphological features of the vehicle trajectory and how it is affected by the highway geometry were analyzed.

Results and conclusions The following were observed: i) Typical track patterns were determined according to features of LDRT profiles, four patterns for left-hand bends and five patterns for right-hand bends, which can be used to identify crash prone position and reveal the mechanism of crash. ii) Inertia may cause the vehicle to move too close to the outer side of the curve after a cut, for which reason the driver has to correct the trajectory, although overcorrection may move the vehicle into the oncoming lane. iii) A higher speed at curve entry adopt by the driver could result in a larger encroachment into opposite lane or shoulder. iv) The smaller the radius of the horizontal curve, the more frequently the trajectory entered the oncoming lane. These findings could provide a better understanding of the track behavior of passenger cars, judge the safety implications of driver behavior, and thus identify crash prone positioning and the potential mechanisms of head-on crashes, run-off-road and guardrail collisions.

Keywords Vehicle trajectory · Track, natural driving · Driving behavior, road safety · Oncoming lane occupation · Lane departure

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1 Introduction

The trajectory of a vehicle is an output of the "driver–vehicle–road" system under the synergistic effects of the driving behavior, road geometry, vehicle performance, and pavement conditions (friction coefficient and evenness). Vehicle trajectory provides a basis for classifying driving behaviors, highway horizontal alignments design, and cross section designs, and is also an indicator of road driving safety [1]. Vehicle trajectory also affords a means of evaluating the coordination among the driving behavior, alignment/roadside environment, and accident risk of a particular road section. This is because an accident—such as one involving the vehicle running off the road or colliding head-on with a roadside fixture—can be described based on the lateral location characteristics of the vehicle trajectory.

The trajectory of a vehicle mainly describes the lateral positional relationship between the vehicle and the highway geometry. A change in the positional relationship is usually due to the steering behavior of the driver when the vehicle enters a curve. Thus, the trajectory characteristics along a horizontal curve and their determinant factors have attracted significant research attention. Off-road observations was the popular method to obtain the lateral position of the running vehicle. With this method, the selected bend was divided into smaller segments on the basis of the geometry features of the bend; test personnel then recorded the position of the vehicles on each cross-section as they passed by, the example shown in Fig. 1 illustrated the measurement of vehicle path using three or five points. By this method, Thomas and Taylor [2] in Louisiana observed that the trajectory deviated toward the inner side of the curve when the vehicle enters a curve. Glennon and Weaver [3, 4] suggested that the curve radii and the speed and initial position of the vehicle when it enters a curve significantly affect the trajectory shape, with the shape also varying with the type of vehicle. Krammes and Tyer [5] measured the lateral deviation of the trajectory at the midpoints of different horizontal curves on a two-lane highway, and found that the lateral deviation of the trajectory can be increased by the use of road markers. Weise et al. [6] analyzed the effects of few factors—sight distance, trajectory lateral deviation, and coefficient of pavement adhesion—on driving safety over curved sections of roads. Garcia and Diaz [7] also found that the trajectory of a vehicle was poorly consistent with the centerline at a bend. For instance, the trajectory curvature was observed to be significantly greater than the designed curvature of the bend. Steyer et al. [8] reported that drivers do not strictly follow the centerline of lanes, and that the curve radius and deflection angle significantly affected the lateral deviation of the vehicle trajectory. Based on the measured lateral distance between the vehicle and the edge line of the highway, Spacek [9] divided the trajectory shape into six types, namely, ideal, normal, cutting, corrected, swaying, and drifting. Tsyganov et al. [10], Sun and Das [11] showed that the edge line affected the trajectory on a narrow road and reduced the risk of accident at a curved section. This phenomenon was proved by a survey conducted by Donnell et al. [12], who also found that a driver moved closer to the inner side of a curve when turning right at night compared to during the daytime. Finley et al. [13] also observed that a driver tended to run near the centerline of a road with narrow hard shoulders or rumble strips on the shoulder.

Driving simulator is another important tool for analyzing driving behavior and trajectory. Blana et al. [14] found that drivers tended to drive toward the centerline of a two-lane highway when at high speeds. Ben and Shinar [15] created different driving situations to investigate the trajectory of a vehicle. They found that the lateral deviation of the trajectory at a sharp bend was greater than that at a gentle bend, and that the trajectory was closer to the centerline when guardrails were on the sides of the road. In contrast, Bella [16] showed that the existence of guardrails did not affect the driver's trajectory or speed. Rosey and Auberlet [17] analyzed the lateral location of a vehicle trajectory on a straight slope (including one with a convex vertical curve) with different types of markers and guardrails, and found that various trajectories could be used to identify undesirable highway geometries. Xu et al. [18, 19] established two measurement indices, namely, mid-curve speed increment and mid-curve trajectory radius increment, for describing the cutting effect, and analyzed the sensitivity of a vehicle trajectory to a change in the geometric features of a curve. Gemou [20] conducted a comparison experiment with a semi-dynamic driving simulator and an equipped vehicle in real traffic conditions, and found that drivers tended to drive towards the right edge of the lane more often in the real traffic conditions than in the driving simulator.

Another aspect of researches are the work related to the path predicting, i.e. the trajectory decision making, which is the core of the steering models. The exploring random tree approach was employed by Boyer and Lamiraux [21] and Kuwata et al. [22] to search a feasible solution of a target trajectory for the next moment within a driving space at the front. In the real world, different drivers have individual driving styles, and they display different behavior in trajectory selection. Some researchers attempt to distinguish the different drivers when they establish their trajectory planning models. Xu et al. [23, 24] proposed a trajectory decision strategy referred to as "point selection on preview cross section," and developed target trajectory decision models of typical driving patterns for mountain highways with complex shapes.

There are several research gaps according to the descriptions of the previous studies' findings related to the vehicle trajectories: i) as seen in Fig. 1, only the lateral locations at a few cross sections along the road were considered, such as at the entrance, midpoint, and exit of a curve. Indeed, many studies only analyzed the midpoint. Because the lateral relationship between the trajectory and the road may change multiple times along a curve measuring dozens or even hundreds of meters, it is difficult to use the lateral locations at only several points to describe the trajectory shape or determine the precise trajectory pattern. ii) Some studies have reported that the geometric features of a roadway, such as the curve radius and deflection angle, affect the trajectory deviation. However, the exact variation of the trajectory deviation with the curve geometry could not be established because of the small number of experimental samples and data scale. iii) The analyzed routes in existing researches were almost in level or level-hilly terrains, therefore only bends with small or medium deflection angles were considered, although real-life drivers frequently encounter curves with larger deflection angles on complex mountain highways.

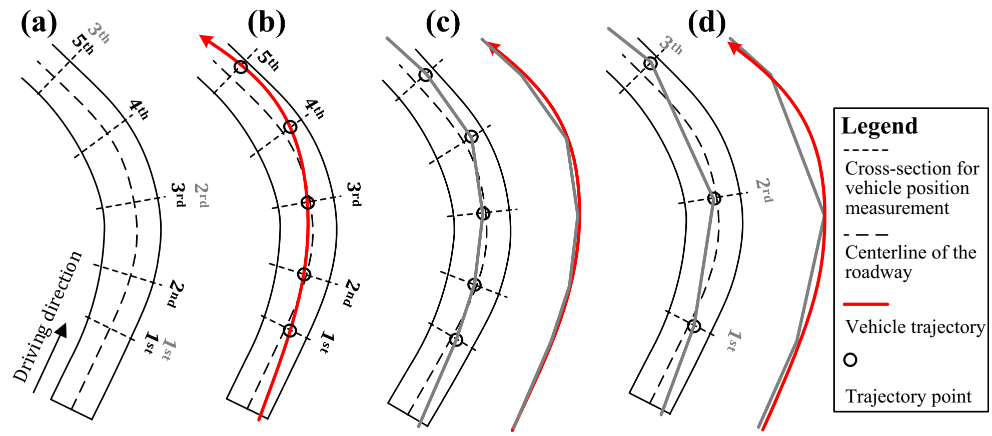


Fig. 1 The method used in trajectory measurement in the existing researches: (**a**) the cross-section within curved area for recording the vehicle lateral position by roadside observation, (**b**) the trajectory of a car when passing the bend, (**c**) record the vehicle lateral position, approximated the vehicle path by linking five points; (**d**) vehicle path was approximated by linking three points

In the present study, field driving experiments were performed under natural conditions on mountain highways with complex alignments. This included on-road vehicle testing and the use of vehicles equipped with test instruments. The continuous trajectories of various types of vehicles including sedans were acquired, and the typologies of the trajectories were examined based on their shape and lateral positions over curved road sections. Typical morphology of each track pattern as well as feature points within curve areas were presented, the behavior lane departures and the reasons why drivers occupy the oncoming lane was also investigated, and the risk of lane departures were analyzed. The findings of this study contribute to enact safety countermeasures to regularize the track and to reduce lane exceeding, which can be used to lessen the head-on collisions caused by a vehicle encroaching on the oncoming lane. And in general level our findings are expected to provide basic data and valuable references for safety facilities design of mountain highways, micro-study of driving behaviors, traffic accident analysis, and traffic operation management.

2 Experimental scheme and method

2.1 Test roads

Four mountain National/Province roads were considered in this study. These roads are all two-lane, narrow hard shoulder, and with complex combinations of horizontal alignment (with complex shapes). Table 1 gives the main technical parameters of the roads. Multiple design standards were adopted for road 3 and road 4 that extended through different districts. Thus, the values of parameters such as pavement width and lane width varied when the design speed changes. China road design standard "*Technique Standard of Highway Engineer*" [25] specifies five classification and six design speed for highway: freeway, first-, second-, third- and fourth-class highways; 120, 100, 80, 60, 40, 30 and 20 km/h design speed. More than two design-speeds are provided for one classification to select according to the terrain, construction investment, land utilization and predicted traffic volume. For instance, design speed of 30 and 40 km/h are available for third-class roads, and 20 and 30 km/h are available for four-class roads. And just like any other countries, Chinese design standard specifies the minimum allowed curve radii and allowed length of curved section. Figure 2 shows the horizontal alignment of four test routes that extracted from Baidu Map software, where the route of Road 1 dwells along one side of Jialing River.

The present study focused on the trajectory characteristics of free-flow driving with no roadside interference. The test drivers could drive freely with very little or no roadside interference over most of the considered road sections because of the very low traffic volume. However, at locations near village fairs and towns, the traffic volume was higher and the drivers encountered interferences from other vehicles, pedestrians, and roadside stall-keepers. The data for such locations were excluded from the data analyses, as well as those for situations involving overtaking.

Horizontal curve is the most common alignment unit of mountain roads, and the ratio of the curve length to the road length can reach as high as 60%–85%, sometimes higher. Negotiating curves is thus a common part of driving on mountain roads. Moreover, the tangent between two adjacent curves may be short, and this affects the trajectory shape along the tangent. Therefore, the present analysis mainly focused on the trajectory characteristics along the curved sections of the considered roads.

2.2 Experimental apparatus and data collection

The test roads were all two-lane mountain roads with very few or no tunnels, and conforming with the trends of nearby hills and rivers. Thus, the VBOX 3I system produced by Racelogic Company in the UK (which integrates a Differential Global Positioning System (DGPS) module), was used to obtain the vehicle trajectories, as shown in Fig. 3. The actual accuracy of

Table 1 Main technical parameters of test roads

Road no.	Name of test highway	Pavement width (m)	Technique Standard	Design speed (km/h)	Length of the road (km)	Minimum radius (m)	Test vehicle type
1	N212 Beibei-Hechuan section	7–8	Third-class	40	26.8	30	Buick Firstland GL8
2	P205 Dazu-Tongnan section	7–9	Third-class	30–40	45.2	30	Mercedes Benz Vito
3	P201 Fengjie-Wuxi section	6–8	Fourth- and Third-class	20–40	74.8	20	Mitsubishi ASX
4	P103 Fengjie-Yunyang section	6–8	Fourth- and Third-class	20–40	121.9	20	Mitsubishi ASX

VBOX in mountain road environments can achieve 40 cm. The sampling frequency was set to 10 Hz, and the DGPS receiver was fixed to the top center of the vehicles. A camera mounted on the front window was used to record the environment right ahead of the vehicle. Another camera on the daughter board on the right-front side was used to record the location of the tires relative to the roadside, which can be used to determine the lateral distance from the vehicle centroid to right edge line of the road, and then used to calibrate the accuracy of the localization of VBOX 3I.

In recent years, private cars (small passenger cars) have accounted for the largest proportion of vehicles on China roads. Passenger cars in China mostly fall into the following categories: hatchbacks, sedans, SUVs, minivans, commercial vans (MPV), and off-road vehicles. Among these, the proportions of minivans and off-road vehicles have decreased in recent times while that of SUVs has been on the increase. On rugged and curvy mountain roads SUVs have the highest speed due to their better dynamic performance, while the speed of MPV is slightly lower than other cars because of their large number of seats and unladen mass. Therefore both SUVs and commercial vans can be considered representative models, and were then selected as the test vehicles in this study, they were: Mitsubishi ASX (2.0 L, automatic transmission, four-wheeler, five seats, wheel base 2670 mm, Length/Width/Height (LWH) 4295 × 1770 × 1625 mm, engine P_{max} 123 kW, unladen mass 1495 kg), Buick Firstland GL8 Business (2.4 L, seven seats, LWH 5266 × 1878 × 1772 mm, wheel base 3088 mm, P_{max} 137 kW, unladen mass 1910 kg), and Mercedes Benz Vito Business (2.5 L, seven seats, wheel base 3430 mm, LWH 5223 × 1901 × 1872, P_{max} 140 kW, unladen mass 2270 kg). Another reason for the choice of MPVs is their spacious interior space, which can contain more experimenters. The matching of the vehicles with the considered roads is detailed in Tab. 1. The car used in this study were rent from car rental agencies, they were purchased within the last 2 years and in a good maintenance levels.

The trajectory and horizontal coordinates of the edge lines and centerlines were both required to acquire the relationship between the trajectory and the road geometry. The test roads in this study were constructed in the middle of the last century, and their design data have been lost, and therefore, the horizontal alignments of such roads were obtained by parameter fitting. The basic procedure involved the following steps: i) The road section was opened in Google Earth and adjusted to an appropriate scale. The length of a randomly chosen line was then measured using the "ruler" tool. ii) High-definition images of the road in Google Earth were imported to AutoCAD 2014. iii) The radii of the horizontal road curves were fitted by the three-point method to determine their values to scale. iv) The lengths of the curves, spirals, and tangents were estimated. By comparing the real value and estimated

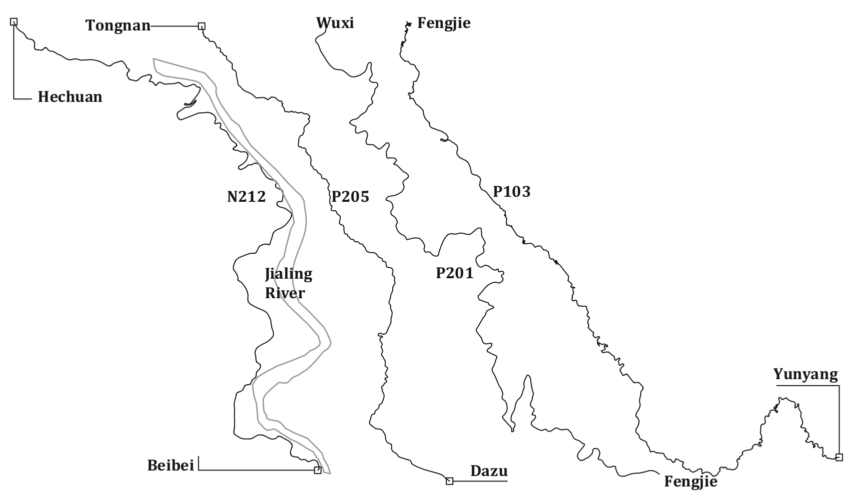


Fig. 2 The test route with complex alignment used in this study

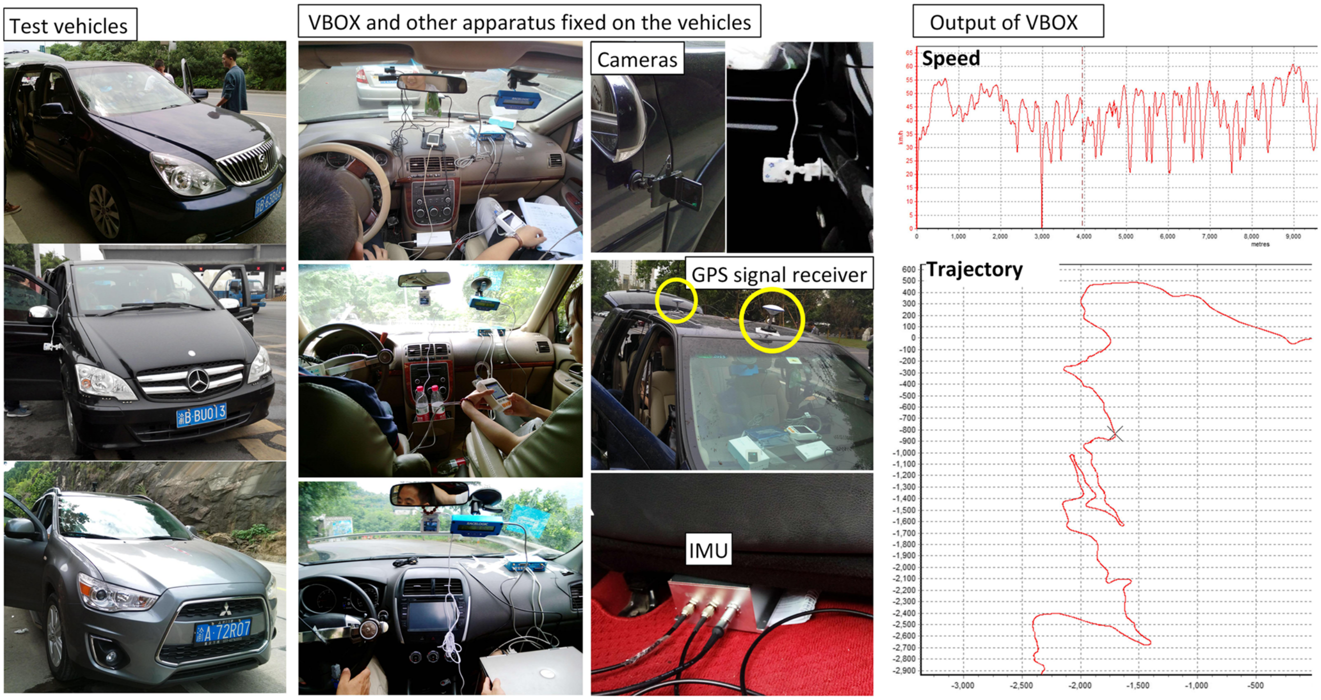


Fig. 3 Driving test using passenger cars under natural driving conditions

values of the alignment elements of another given road section outside the test roads with known geometric parameter, the fitting error of the curve radii and the deflection angle (△) can be reached to 5%–8% and <5%, respectively. Both values satisfied the analytical requirements of the study.

2.3 Participants and experimental scheme

Three to four participating drivers were assigned to each test section, and each driver was required to drive back and forth the allocated test section once. Road 4, the longest test road, was divided into two test sections. Almost all of the participants would ask the aim of the driving test before a test started, and we told them the purpose of the test is to collect the dynamic parameters of the car to evaluate the vehicle's design quality, i.e., they don't know the real purpose of the study. The participants were told that they were allowed to drive the vehicles according to their usual habits and styles. And no additional request, hint, or implication was provided to the drivers, so they steered their cars under naturalistic conditions. The collected vehicle trajectories thus reflected naturalistic driving behaviors. The total number of participants was fourteen, they were skillful male drivers with legally acquired driving licenses. Their ages were within 22–55 years, with an average of 36.75 years, while their actual driving experiences ranged between 2 and 24 years, the average being 10.87 years.

The participants employed in this study were provided by car rental agencies, as well the test cars. For each driving test, these participants alternately drive the car to head for the field test site from our university (several hours' drive), and therefore, they became familiarized with the car before the experiment proper started. And about twenty to thirty minutes were provided to them to get familiar with the environment of the analyzed road before we begin a test. Moreover, all the participants have rich experience in mountain roads driving because two-lane mountain roads are very common in Chongqing, China. Although their familiarity with the specified roads were not as good as that of local drivers.

2.4 Description of lateral location of trajectory

The typology of a vehicle trajectory mainly refers to the lateral positional relationship between the trajectory and the edge line or centerline of the road. The lateral deviation (LD) between the trajectory and the centerline of the lane was the most commonly used index in previous studies. This, however, constitutes a very serious shortcoming because roads designed in accordance with different technical standards have differing pavement widths and traffic lane width. Moreover, the pavement widths at straight and curved sections of a road may significantly differ. It is thus inappropriate to describe the lateral location of a vehicle trajectory based on the LD. In the present study, the LD was replaced with the lateral deviation rate of the trajectory (LDRT).

$$LDRT = d_1/w_l \quad (1)$$

Where d_1 denotes the lateral distance between the vehicle centre point and road centerline, and w_l denotes the width of the traffic lane where the vehicle travels, see the third row and third column of Table 2. This parameter allows for varying lane and pavement widths.

In this study, the vehicle trajectory is defined by the movement of the vehicle centroid. The positional relationships between the vehicle and the pavement markers such as the centerline and edge line for different ranges of the LDRT is list in Table 2.

2.5 Definition of track patterns

The driving speeds measured on complex mountain roads in this study using the VBOX with 10 Hz sampling frequency of the on-board DGPS were 30–75 km/h (10–20 m/s). This implies a distance of 1–2 m between two adjacent trajectory sampling points. Then the interpolation method proposed by Shao et al. [26] was introduced to obtain the continuous trajectory of the test car, by interpolating the sampling points. The trajectory and road markers were then superposed in the same coordinate system. The initial location of the vehicle on the road at the beginning of a test drive was precisely marked to ensure accuracy of the relative locations of the trajectory and road markers after their superposition. The LDRT was computed at regularly spaced cross sections along the road to obtain the continuous LDRT curve. The complete process is illustrated using an actual data measured on a sharp bend, as shown in Fig. 4. By comparison of the results, it was determined that the lateral positional relationships between the vehicle trajectory and the pavement markers could be accurately determined when using measurement cross sections spaced at 3–5 m.

Trajectory points maybe across the edge line of the roadway on certain locations such as the segment with trees of luxuriant branches on roadside and the segment beneath a bridge, due to the reduction in the number of the satellite conveying the GPS signal. In this case, the video images from the cameras mounted on the right-front wheel fender and front windshield were used to determine the lateral distance from the vehicle centroid to the edge line or center line of the pavement, as shown in Fig. 5. The lateral distance was then used in the calibration of the vehicle position at this position, and was used as an alternative to the track from DGPS at locations where the number of received GPS satellites less than six. Overall, about eight to 12 % of the total travel length needs to use this procedure.

The curves on the mountain roads exhibited different geometric features, plus the diversity in trajectory selection, there would be a large number of possible combinations of the "bend + trajectory." Therefore, it was difficult to quickly determine the pattern and nature of the driving behavior by performing a direct analysis of the trajectory shape on the bends. In contrast, the LDRT does not depend on the shape of the curve. Therefore, in this study we interpreted the driver's trajectory selection behavior based on the variation features of LDRT, and recognized the track patterns by clustering the LDRT profiles measured from different bends on the basis of the following features of LDRT profiles:

- The number of peak points or inflection points or turning points;
- The trend of LDRT curve depending on the travelled time before the first peak point, rise or decline;
- The trend between two neighboring main peak points or turning points;
- The similarity in the shape of LDRT profiles.

3 Results

3.1 Analyzed curves

About one hundred curves were selected randomly from the total curves along the test roads, and LDRT profiles of these curve were calculated. In this section, 52 small-radius curves were selected again among one hundred curves as examples based on the typicalness for their LDRT shapes. Among these, 26 were left bends and the other 26 were right bends, as indicated in Table 3, where R is the radius of bend; Δ is the deflection angle of bend; V_e is the speed at curve entry.

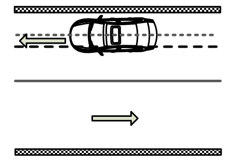
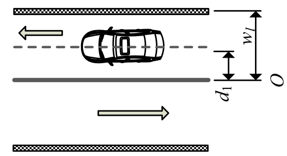
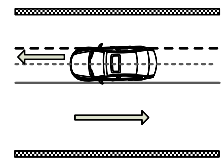
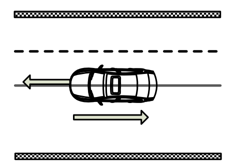
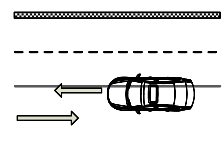
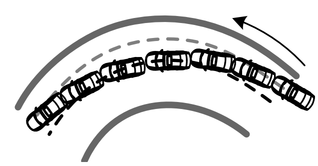
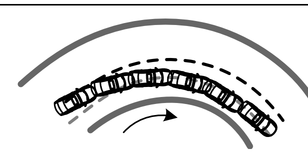
3.2 Trajectories on left-turning curves

3.2.1 Track patterns on left-turning curves

Figure 6 provides four typical patterns of trajectory shape for the 26 considered left bends, which determined by the characteristic of the LDRT profiles. In real world driving, the drivers' trajectories along the curves can be affected by the trajectories on the preceding and succeeding tangents, thus, the LDRTs at 1 s before entering the curve and 1 s after exiting it were also respectively calculated.

Of which, LDRT–time profiles in Fig. 6a1 were derived from the first six left-hand bends. The running time on the different curves varied owing to the differing curve geometries, therefore the different LDRT profiles were interlaced and the feature points were staggered, which made it difficult to determine the overall variation tendency and common control laws. Then they were translated and stretched to obtain a clearer trend and characteristics of LDRT profiles of bends with different geometric features, as shown in Fig. 6a2–a3, from the two figures several features can be grabbed, and we can conclude that: Firstly, each of the LDRT profiles has two inflection points, C_1 and P_1, of which C_1 is the cutting point (apex) and P_1 is the position at which the car being closest to the right edge line of roadway. Secondly, the LDRT values after entering the curves initially decrease monotonically to the minimum value before the mid-curve point

Table 2 Schematic illustration of lateral deviation rate of trajectory (LDRT)

Value range of LDRT	The lateral position of the running vehicle	Illustrated in diagrams
> 50%	The vehicle centroid is located on the right side of the lane, It was observed that drivers steered their cars at the inner side of the lane when navigating a right-turning curve, and at the outer side when navigating a left-turning curve	
= 50%	The vehicle centroid coincides with the centerline of the lane, indicating that the driver strictly runs in the middle of the lane.	
25% < LDRT < 50%	The vehicle centroid is located between the centerline of the lane and that of the road. The left side of the vehicle is about to cross the centerline of the road when LDRT ≈ 25%	
= 0%	The vehicle centroid is located on the centerline of the road, implying that the left side of the vehicle has crossed into the oncoming lane	
< 0%	The vehicle centroid is located on the left side of the centerline of the road, implying that more than half of the vehicle has entered the oncoming lane	
LDRT decreases monotonically	The vehicle is approaching the inner side of the lane at a left-turning curve (i.e., cutting), or approaching the outer side at a right-turning curve	
LDRT increases monotonically	The vehicle is moving toward the outer side of the lane at a left-turning curve, or toward the inner side at a right-turning curve (cutting)	

(approximately at the middle of the distance along the curve). Thus, the apexes of the bends could be considered to be located before the mid-curve point. The lower the LDRT at C_1, the greater the degree of curve cutting, which also differed among the drivers (Fig. 6a1). For example, the LDRT on Curve L1 was <25%, indicating that the left tires of the vehicles encroached on the opposite lane. Thirdly, the LDRT values gradually increase after C_1, reaching the maximum value at P_1 before the end of the curve, indicating that the vehicles had moved from the left to the right side of the lane. Fourthly, the LDRT values tend to decrease again after P_1, in what is referred to as the recovery phase, in which the status before entering the curve is restored.

Figure 6a4 and a5 show two typical shapes of this trajectory pattern, and the point C_1 and P_1 were marked on this bend to give a visual presentation for an easier understanding. In

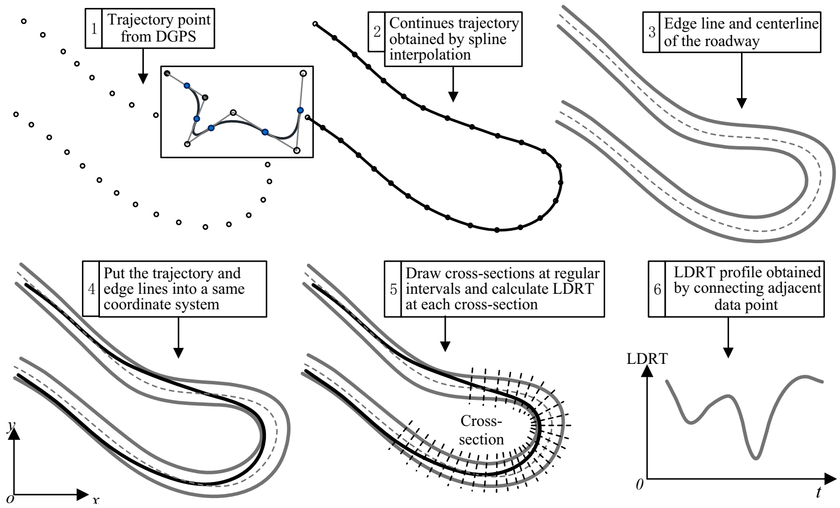


Fig. 4 Obtaining continuous vehicle trajectory and determining the lateral deviation rate of trajectory (LDRT)

general, a too close distance between vehicle and road edge at point P_1 is more likely to occur when a higher speed at curve entry adopt by the driver.

LDRT Profiles and the track in Fig. 6b1–b3 exhibit the second pattern of vehicle trajectory, derived from left-hand bends of L7-L13. An outstanding feature of this driving pattern is that the cutting point C_1 appears on the middle of the bend, and P_1 no longer occurs within curve areas. The third common pattern of vehicle track is presented in Fig. 6c1–c3, unlike the first two patterns, drivers don't recover their vehicle to the original lane after they cut the bend, whereas keeping their vehicle in the opposite lane, which cause a longer time of vehicle exposed in dangerous situation. The last track pattern observed on left bends is provided in Fig. 6d1–d4, the LDRT profiles changes in a completely opposite manner compared with Pattern I, and result in a great difference of this track: P_1 appearing in the front of C_1, that is, drivers approach to the outside of the bend at curve entry, and cut the bend in the second half of the bend. By this way, drivers can gain a minimum travel time throughout the bend, and this driving pattern is often seen on sharp bends with large deflection angle. Of the four patterns above, Pattern I and Pattern III are more frequently observed on younger drivers or unskilled drivers who have less driving experience, they might have an inaccurate perception of bend curvature and length, and thus choose an inappropriate speed and path.

3.2.2 Risk analysis of track behavior

For the perspective of traffic safety and collision prevention, the behavior of lane departures can be classified into two categories: active departure and passive departure. Of which, the former is a driver's planned operation when the driver is convinced of the risk of lane departure within their control, so the departures at position C_1 of track pattern I-IV and P_1 of pattern IV all can be categorized into the active departure. Whilst the latter is an unintended departure owing to a larger inertia of the quickly moving vehicle, that is, the vehicle moved towards the outside of the curve after curve-cutting is finished, and the departure at P_1 of track pattern I falls into this category. Pattern III is considered another dangerous track type, because the encroachment of opposite lane after C_1 can be grouped into passive departure. Although the risk of

Fig. 5 Using the position of right tire on the pavement to determine the lateral position of the test car

Table 3 Geometric parameters of the curves used in Section 3.1 and 3.2

Curve No.	Deflection	R (m)	Δ (°)	V_e (km/h)	Curve No.	Deflection	R (m)	Δ (°)	Ve (km/h)
L1	Left hand	45	65	44	R1	Right hand	24	40	46
L2	Left hand	57	50	45	R2	Right hand	55	60	47
L3	Left hand	75	30	56	R3	Right hand	76	40	48
L4	Left hand	56	70	47	R4	Right hand	31	45	36
L5	Left hand	88	30	45	R5	Right hand	55	60	49
L6	Left hand	65	30	60	R6	Right hand	42	60	41
L7	Left hand	70	35	53	R7	Right hand	100	25	/
L8	Left hand	67.3	50	47	R8	Right hand	100	25	56
L9	Left hand	46.3	50	42	R9	Right hand	70	40	55
L10	Left hand	79	70	42	R10	Right hand	65	35	58
L11	Left hand	65	30	58	R11	Right hand	100	30	53
L12	Left hand	69	35	50	R12	Right hand	70	40	45
L13	Left hand	70	35	/	R13	Right hand	133	50	38
L14	Left hand	88	30	30	R14	Right hand	72	90	/
L15	Left hand	60	35	52	R15	Right hand	163	30	62
L16	Left hand	60	60	44	R16	Right hand	74	60	53
L17	Left hand	55	40	50	R17	Right hand	65	55	40
L18	Left hand	70	35	54	R18	Right hand	85	63	55
L19	Left hand	60	35	/	R19	Right hand	76	40	/
L20	Left hand	68	35	/	R20	Right hand	46	135	/
L21	Left hand	46	50	/	R21	Right hand	37	100	34
L22	Left hand	93	70	55	R22	Right hand	46	135	47
L23	Left hand	72.3	90	52	R23	Right hand	42	45	51
L24	Left hand	32.4	110	32	R24	Right hand	70	180	/
L25	Left hand	55	40	/	R25	Right hand	37	100	33
L26	Left hand	32	110	/	R26	Right hand	72	70	/

heading on with the car driving on the opposite lane may exist in the active departures, such as near the point C_1. However, the risk of scraping or heading on the barrier mounted on the right side at point P_1 because of passive lane departure needs more immediate attention.

3.3 Trajectories on right-turning curves

3.3.1 Track patterns on right-turning curves

Figure 7 exhibits four typical track patterns and their corresponding LDRT profiles for twenty-six right-hand bends list in Table 2. From Fig. 7a1–a3, it can be observed that the LDRTs of Pattern I initially increases progressively, indicating that the vehicles approached the inner side of the curve, referred to as curve cutting. The LDRTs begin to decrease gradually after C_1, reaching a minimum value at P_1 after the mid-curve point and before the curve end. Thereafter, they begin to increase again. The manner of changing trend of vehicle lateral position in Fig. 7a4–a6 is very close to that of Pattern I on left-hand bends.

With the Pattern II in Fig. 7b1–b4, drivers cut the bend and the cutting point C_1 occurs near the middle of the bend. In our measurement, this track type make up the largest percentage of the population, especially on the bends with deflection angle less than 60°. Track Pattern III in Fig. 7c1–c3, at first glance, appears a similar shape with track Pattern II. However there exists a crucial distinction, i.e. without an apparent cutting point in this pattern, instead, drivers keep their cars close to the inner side within curve areas after they enter the bend. Also, like the last track Pattern on left-hand bends, track Pattern IV in Fig. 7d4 are often seen on the very skilled male drivers.

The track shape of Pattern V is markedly distinct from the tracks of Pattern I to Pattern IV, drivers steered their cars toward the outside near the mid-point of the bend after they enter the bend. With this pattern, drivers may get a better sight

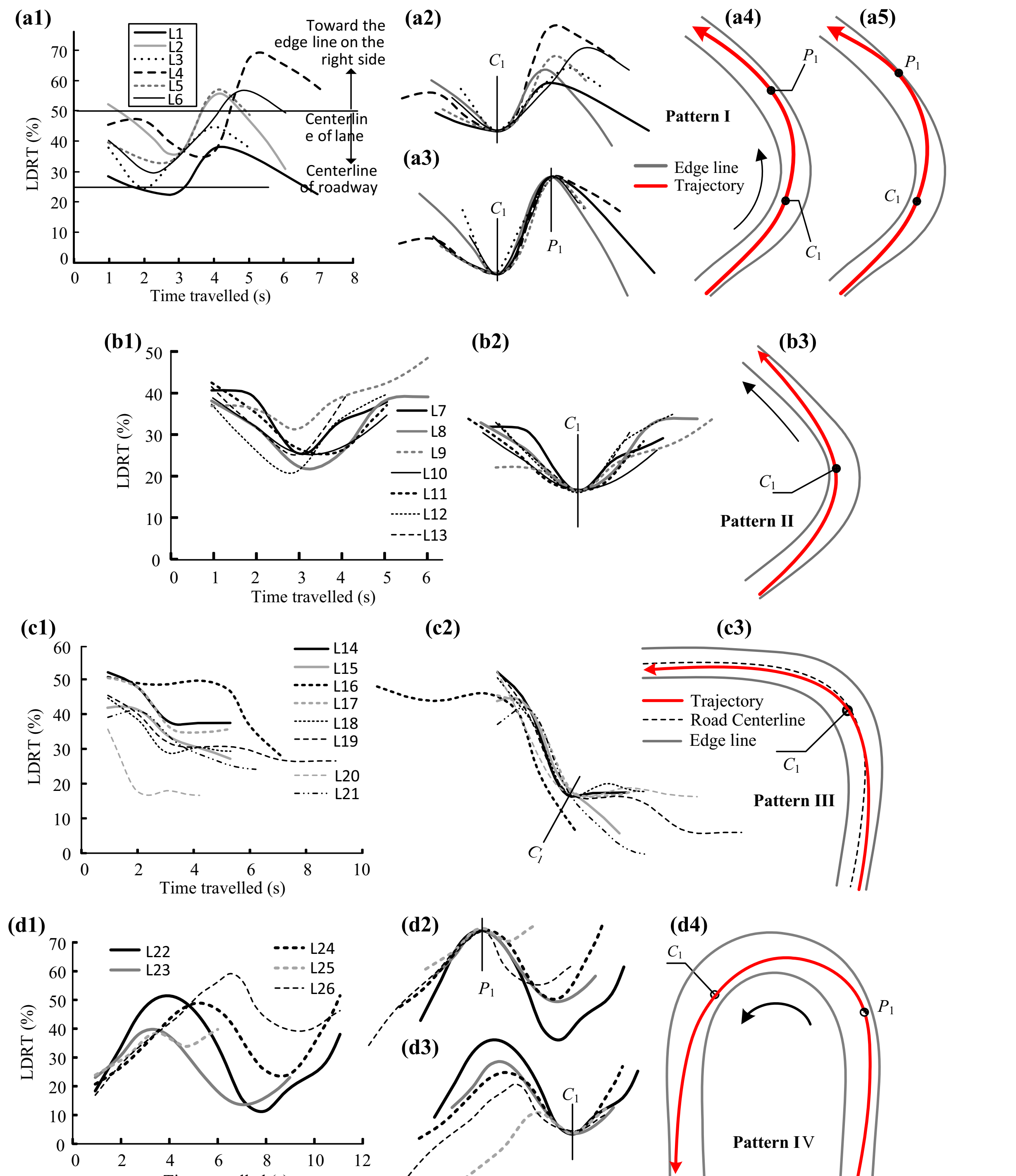


Fig. 6 Trajectory shape of four typical patterns and their corresponding LDRT profiles for left bends: (**a1**-**a5**) Trajectory pattern I on left-hand bends; (**b1**-**b4**) Trajectory pattern II on left-hand bends; (**c**) Trajectory pattern III on left-hand bend; (**d**) Trajectory pattern IV on left-hand bends

distance at curve centre, however, a risk of collision with opposite traffics is correspondingly brought out to drivers. This pattern, along with Pattern I, are more common in drivers who have less driving experience.

3.3.2 Risk analysis of track behavior

From the aspect of collision possibility at the position near P_1 for track Pattern I, IV and V, car body would be beyond the

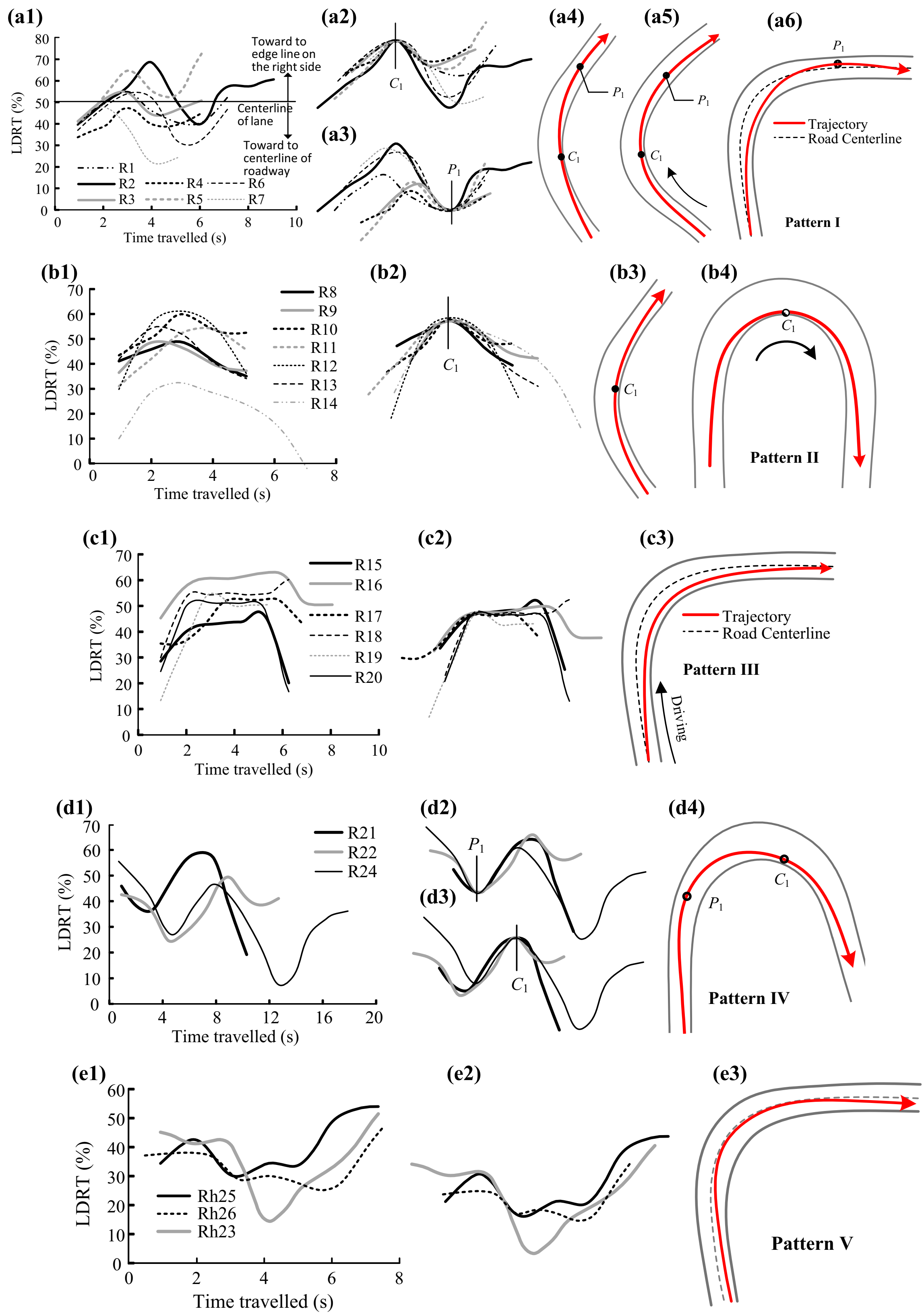


Fig. 7 Trajectory shape of four typical patterns and their corresponding LDRT profiles for right-hand bends: (**a1**–**a5**) Trajectory pattern I on right-hand bends; (**b1**–**b4**) Trajectory pattern II; (**c**) Trajectory pattern III; (**d**) Trajectory pattern IV and (**e**) Pattern V

centerline of the roadway, and on the surface, which might have caused a collision with the vehicle running on the opposite lane. However, the possibility of heading on collision for Pattern IV is much smaller than that on Pattern I and V. The reason is that approaching the outside of the bend has been planned by the driver when he/she entering the bend, that is, the lane departure of Pattern IV is possibly a planned steering operation for the driver. In particularly, the locally highest curvatures generally occurred around P_1 with track Pattern V because of the contribution of the steering corrections, and the increased lateral acceleration of this track type can cause the car rollover or sideslip. Of the five presented track patterns in Fig. 7, Pattern II and III can be considered as the "normal" track because their corresponding active lane departure appears in the middle of the bend, and no passive departure occurs. Using this criteria, Pattern II in Fig. 6 above can be defined as the "normal" track for the left hand curves.

There exists a connection between speed and trajectory shapes. A higher speed leads to a larger inertia of running vehicle, which could "force" the drivers to cut into the opposite lane or the shoulders. Therefore, from this perspective, reducing the vehicle speed before it entering the curve entry is an effective measure to regularize the track behavior of passenger cars.

3.4 Effect of horizontal curve radius

The curvature radius is an indication of the sharpness of a horizontal curve, it can significantly affects the perception and judgment of drivers, and thus affects the track behavior. The LDRTs during the negotiations of eighteen curves of differing radii selected from the test roads were presented in Fig. 8a–f to illustrate this effect, where the three curves in each sub-graph correspond to the same driver. Only very few of all the curves considered in this study had radii larger than 200 m (the roads have complex alignments and were constructed using lower–ranked technical standards). The radii of the 18 curves were divided into three groups: 10–50 m, 50–100 m,

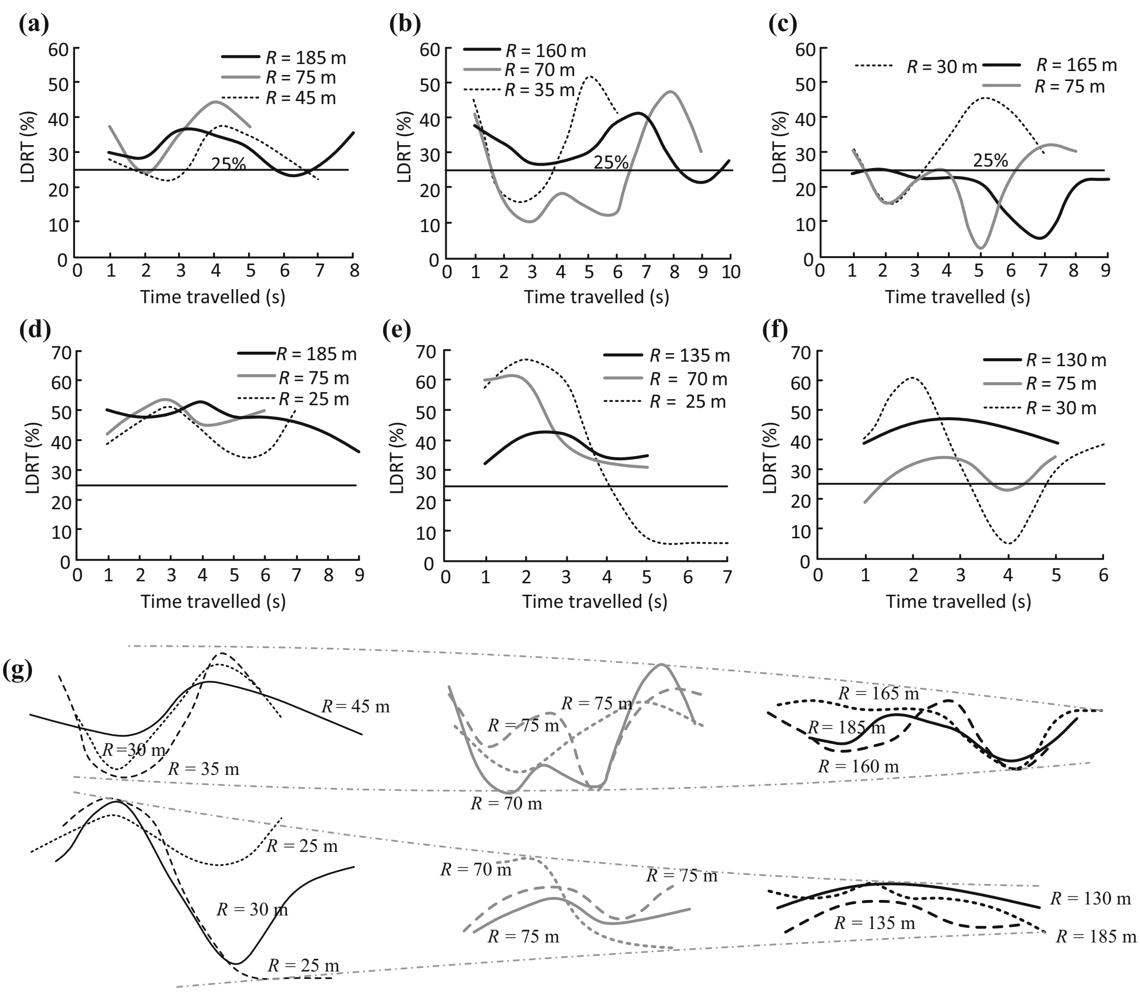


Fig. 8 LDRT profiles: (**a**) driver #1, left bends; (**b**) driver #4, left bends; (**c**) driver #7, left bends; (**d**) driver #1, right bends; (**e**) driver #4, right bends; (**f**) driver #7, right bends; (**g**) clustering of LDRT profiles based on the curvature radius

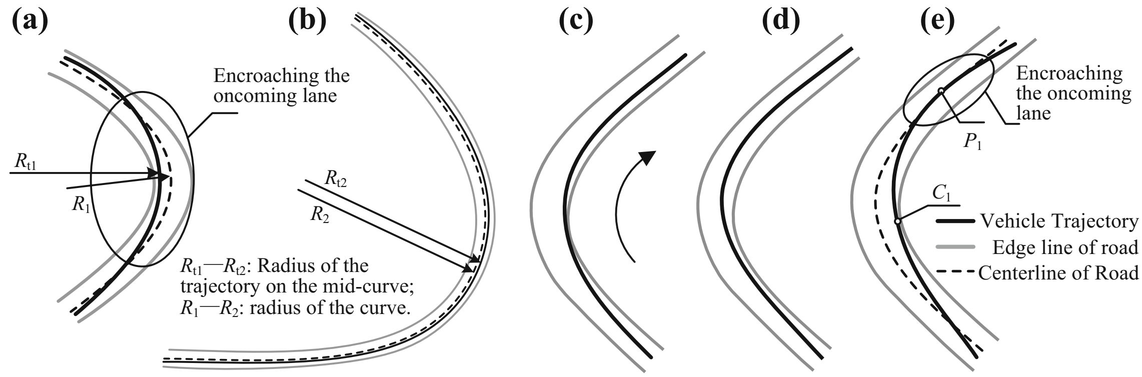


Fig. 9 Trajectory at (**a**) sharp left bend and (**b**) large-radius left bend; (**c**–**e**) typical trajectories at small-radius right bend

and 100–200 m. The closeness of the deflection angles of the curves (60–100°) was considered in their selection to eliminate the effect of the parameter.

It can be observed from Fig. 8a–f that the least fluctuations of the LDRTs correspond to the curves with the largest radii, indicating that the variation of the lateral relative location of the trajectories decreased with increasing radius; i.e., the trajectories fitted better with the highway alignments. Moreover, most LDRTs are below 25% and close to zero over a certain period, indicating that, based on the judgment standards in Section 2.4, occupation of the oncoming lane at bends is a common driving behavior on two-lane mountain roads, especially at small-radius curves. In addition, when a vehicle enters a right bend with a small radius (see Fig. 8d–f), the LDRT rapidly increases, implying that the driver quickly approaches the inner side of the curve.

Figure 8g shows the result of clustering the LDRT profiles based on the curve radius, more clearly reflecting the effect of the radius on the LDRT. It indicates that a driver significantly cuts the bend when driving through a sharp bend by, while this curve-cutting behavior is replaced by curve following when negotiating a large-radius bend owing to the inability to increase the trajectory radius, as shown in Fig. 9a–b. Three typical shapes of trajectories at small-radius right bends are shown in Fig. 9c–e. Generally, a vehicle driven at a high speed has a small trajectory similar to the last one in the figure. The occupation of the oncoming lane occurs when the vehicle is about to exit the curve, which may cause a head-on collision with the opposite traffic.

Figure 10a, b show the scatter data of trajectory transection rates (TTRs) versus curve radius. Here, TTR is the ratio of the pavement width occupied by the driver to the total pavement width at the negotiated bend, equivalent to the maximum LDRT minus the minimum LDRT (see illustration in Fig. 10c). Using the SPSS 19.0, a statistics analysis software, nonlinear regression models of TTR are obtained, and of which, the first three equations with highest goodness of fit (R^2) are list in Table 4, and their corresponding fitted curves are plotted. Sample size for left-hand and right-hand bends are 71 and 61 respectively. In Table 4, b_1 is the parameter used in the regression equations. From the distribution of the scattered data and its corresponding trend lines, we may come to the conclusion that on bends a smaller radius drivers would take a larger pavement width to steering their vehicles.

4 Discussions

Based on the result, the paper proposes safety countermeasures to regularize the track and to reduce lane exceeding, which can be used to lessen the head-on collisions caused by a vehicle encroaching on the oncoming lane. For a running car, the higher speed at curve entry and larger mass of vehicle body, the shorter distance between the vehicle and the right edge line of the roadway (take left-hand bends, for example). So reducing the entering speed is an effective measure to decrease the possibility of scraping or heading on the barrier, which can also lessen the difficulty in trajectory adjustment. Raising the anti-collision performance

Fig. 10 (**a**) TTR with respect to curve radius for left bend; (**b**) TTR with respect to curve radius for right bend; (**c**) illustration for TTR

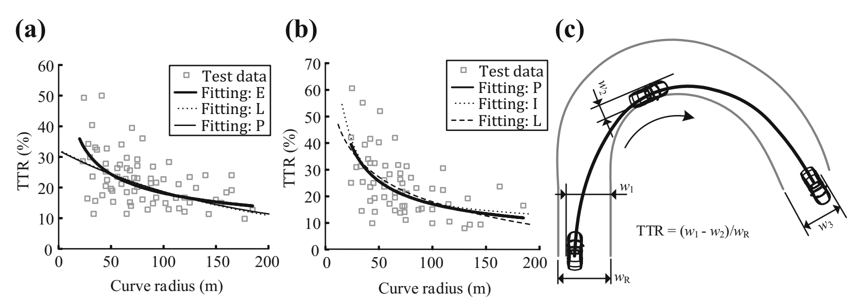


Table 4 Nonlinear regression models for the effect of curve radius on TTR

For left-hand bends						For right-hand bends					
Equations	Constant	b_1	R^2	F	Sig.	Equations	Constant	b_1	R^2	F	Sig.
Exponential (E)	0.326	−0.005	0.395	45.0	0.000*	Power (P)	2.549	−0.587	0.379	35.961	0.000
Logistic (L)	3.071	1.005	0.395	45.0	0.000	Inverse (I)	0.107	7.943	0.363	33.629	0.000
Power (P)	1.274	−0.423	.385	43.136	0.000	Logarithmic (L)	0.833	−0.141	0.358	32.859	0.000

*$P < 0.001$

of roadside guardrails is a countermeasure to lessen the severity of heading on collisions. Besides, erecting the plastic delineators (median separations) or painting the solid double lines on the middle of the roadway can inhibit the behavior of curve cutting effectively, so can be used on situations that lane departure produced by curve cutting has been identified as the cause of heading on collisions. The above three safe countermeasure are presented in Fig. 11.

The factors related to road geometric parameters analyzed in this study are deflection angle, deflection direction and radius of horizontal alignment. Vertical alignment is also a component of road geometry features, which could affect drivers' behavior and vehicles' driving state, especially the driving speed. And a greater the mass of the vehicle is, a bigger impact will be caused. The test vehicles used in this study are 5-seat SUV and 7-seat MPVs, i.e., all belong to the passenger cars. In our observation from the videos recorded by the camera mounted on the front window, drivers are willing to cut curves if no oncoming vehicles on the opposite lanes regardless of whether driving on an uphill or downhill. Take downhill for instance, there are no indications that the slope enable the drivers to steer their vehicle in the middle of the driving width. Therefore, slopes of mountain roads can be considered as an insignificant factor that can affect the track of passenger cars.

The aim of this study was to acquire the behavior and patterns of passenger cars' track on mountain roads featured by complex shapes and low traffic. Driving habits were analyzed under conditions in which the driver was free to choose his trajectory and driving width on the entire pavement, i.e., under a condition that affecting drivers' steering input to their vehicles are factors of driving status of the vehicle and road geometry in front, not the proceeding/succeeding vehicles or other interference from roadside. Data corresponding to scenarios such as vehicle following, overtaking, and curve meeting (meeting a car in the oncoming lane at a curve) were excluded from the analysis, and therefore, the observations and conclusions of this paper are based on data obtained during free-flow driving. The exclusion was for obvious reasons. For example, in the case of curve meeting at a left bend, the test driver was constrained by the oncoming traffic to remain in his own lane, and his/her planned cutting was thus cancelled.

The trajectory of a vehicle is the output of a complex movement mechanism steered by a driver. Thus, using a

Fig. 11 Safety countermeasures for preventing passive lane departures or inhibiting the behavior of curve cutting

given vehicle model, different drivers and driving behaviors (input) will definitely produce different trajectory patterns (output). Therefore, drivers with a wide range of age and driving experience were employed in this study to obtain as many trajectory patterns for two-lane mountain roads as possible. For the same reason, four roads with similar conditions were used to perform the driving test, so that we can extract more driving patterns from naturalistic driving data. Our work are mainly intended to investigate the trajectory patterns on two-lane mountain roads, and focused on the effects of the geometrical factors of the road on the trajectory characteristics. The driver characteristics such as age and driving experience were not discussed, and these factors will be considered in another paper by the authors. Different vehicles of two types were used in this work, including SUV and MPV, the reason for vehicle variability is that the selected MPVs are with seven seats, longer wheel base and heavier unladen mass, which resulting a relatively poor maneuverability and lower travelling speed than SUVs and other passenger car types. Therefore, for road infrastructures design and accident prevention it is a typical vehicle type. And we imagine if MPVs with larger size exhibit a diversity in track patterns, other passenger cars will truly reflect it.

One of limitations of the present study is that the experimental data were obtained from only male drivers. The driving behaviors of female drivers (such as the speed choice, path selection and operation input) on the test roads analyzed in this study which included numerous sharp curves and curved sloping sections might be different from that of male drivers, however, we need field test data to verify it. In a future work, we would perform experiments using real cars and female participants. Another limitation of this study is that the sample of 3-4 participants for each test road perhaps was insufficient, which could result in a consequence that some unknown track patterns may be missed. However, more than ten participants were employed and they finished a round trip test on each road, and therefore, the distance travelled by these drivers approximated 1500 km, which could remedy the defect of insufficient participants sample to some extent. It should also be noted that large vehicles such as buses, coaches, and heavy trucks account for a large proportion of road vehicles, and their spatial trajectory is a main consideration in the design of road geometry. The trajectories of such large vehicles can only be accurately described by multiple feature points owing to their large bodies and long wheelbases. We plan to conduct further study using such vehicles.

5 Conclusions

In this study, field driving experiments were performed under natural conditions on curvy mountain roads. The continuous trajectories of the utilized vehicles and video recordings were obtained and used to determine the continuous profiles of the lateral deviation rates of the trajectories (LDRTs). The effect of the road geometry on the trajectories chosen by the drivers was analyzed, as well as the typologies of the trajectories and the associated accident risks. The major findings are as follows:

(1) Typical track patterns within curve areas were determined according to features of LDRT profiles, four patterns for left-hand bends and five patterns for right-hand bends. Crash prone position and its corresponding accident types were analyzed.
(2) The position of the apex (cutting point) is not fixed for different track patterns, and it may appear at the front of, just in and at the back of the middle of a curve.
(3) With increasing curve radius, the LDRT fluctuation weakens and the trajectory fits better with the horizontal alignments of the road. The smaller the radius, the more frequently the vehicle occupies the oncoming lane. The encroachment on the oncoming lane occurs when the vehicle enters a left bend or exits a right bend.
(4) A vehicle encroaches the oncoming lane on two occasions, namely, during curve cutting and overcorrection. In the second case, the vehicles approaches too close to the outer side of the curve after cutting, and the drivers has to steer back to correct the lateral location of the vehicle. In other words, a vehicle approaches the oncoming lane due to poor steering of the driver.
(5) Based on the feature points within curve areas, the behavior of lane departures was classified into active departure and passive departure, of which passive lane departure might be at a greater risk of collision with roadside barrier and opposite traffic, and requires safety countermeasures to regularize the track.

The findings above contribute to judge the safety implications of driver behavior, and thus identify crash prone positioning and the potential mechanisms of head-on crashes, run-off-road and guardrail collisions. And therefore, effective countermeasures in safety facilities, speed enforcement and driver training could be acquired to raise the road safety. Moreover, our findings may also be useful to automatic drive, which can provide helpful insight into the track behavior of passenger cars and track patterns recognition, and they could be useful in developing an anthropomorphic algorithm to simulate the driving habits of human drivers. The ultimate goal is to produce a human-like self-driving vehicle.

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