Traffic & Transportation

Influence of Urban Underground Spiral Ramp Curve Design on Vehicle Running Performance

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Original Scientific Paper
Submitted: 30 Oct 2024
Accepted: 6 May 2025
Published: 24 Feb 2026

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

ABSTRACT

Urban underground spiral ramps' continuous curves and the monotonous tunnel environment increase driving safety risks and reduce vehicle stability. To clarify the influence of road geometric alignment parameters on vehicle acceleration in urban underground spiral ramp curves, a real vehicle test was conducted on the Jiefangbei Underground Ring Road - Hongyamen Underground Road in Yuzhong District, Chongqing, China. On-board instruments collected acceleration data from 20 drivers to analyse how curve radius and angle affect the vehicle's three-axis acceleration. The results show that: (1) The exit acceleration of the spiral ramp curve is positively correlated with the curve radius and negatively correlated with the turning angle, while entrance deceleration exhibits the opposite trend. (2) Lateral acceleration is negatively correlated with curve radius but positively correlated with turning angle. (3) Vertical acceleration increases with curve radius on upward curves and decreases on downward ones; the opposite occurs with turning angle. (4) Vehicle acceleration differs significantly under varying radii and turning angles. The average exit acceleration is higher for ordinary-radius (or small turning angle) curves than for small-radius (or large turning angle) curves, while the average lateral acceleration exhibits the opposite trend. These findings reveal passenger car driving behaviour characteristics on urban underground spiral ramps, supporting future curve geometric design and safety studies.

KEYWORDS

traffic engineering; driving behaviour characteristics; real vehicle test; urban underground spiral ramp; vehicle acceleration; curve geometric parameters.

1. INTRODUCTION

Urban underground roads feature multiple entrances and exits and a large-scale layout. Its unique underground construction mode has apparent differences from ordinary urban roads in terms of environment, service objects, linear design and other aspects [1]. These underground roads are crucial in alleviating surface traffic congestion, improving network connectivity and reducing accident rates under adverse weather conditions [2]. However, they also bring new safety challenges. The driving risks in urban tunnels are higher than those in highway tunnels, leading to an increased accident rate and higher social costs [3]. Roads often require spiral layouts in areas with sharp terrain changes, which use continuous curves to extend driving distance. Spiral expansion curves are widely used in tunnels, urban roads, interchanges and highways, with spiral ramps serving as a typical example of this design. However, there is no specific design standard for spiral ramps, which means they must be designed based on the linear standards for ring ramps or even branch ramps [4]. As a crucial traffic node of mountainous urban roads, the spiral ramp has the characteristics of constant radius curvature, one-way steep slope and multi-ring large-angle rotation [5]. However, driving speeds often exceed the design limits [6], and speeding remains the primary cause of traffic accidents [7]. Additionally, the ramp's geometric parameters and the driving environment affect the driver's psychological load, increasing operational difficulty and accident risk [8]. Such conditions are especially pronounced in environments featuring continuous longitudinal slopes, tight curves and relatively enclosed underground spiral ramps. Drivers may experience psychological stress and visual distortions related to the bends and ramps, which can impair mental and physical functioning, reducing driving efficiency over time and increasing safety risks. The complexity of an accident can easily lead to secondary incidents [9]. Its design primarily adheres to the *Code for Design of Urban Underground Road Engineering* (CJJ221-2015) and relevant local specifications. However, fully meeting the unique spatial layout and functional requirements is often challenging, leading to issues such as limited linear adaptability, increased safety risks and operational management difficulties [10]. Additionally, the unique alignment of urban underground spiral ramps results in distinct driving behaviours and vehicle operation modes [11]. Although the corner angle and curve radius are geometrically related and can be correlated using the arc length formula, they represent distinct design parameters [12]. The curve radius reflects the degree of curvature and is closely associated with the risk of traffic accidents. The turning angle demonstrates the degree of change in the vehicle's direction, influencing the curve's path length and affecting the duration of the driver's steering operation, which in turn impacts the resulting driving trajectory [13-14]. In actual design, these two parameters typically work together. During the driving process, vehicles are affected by curve alignment factors such as curve radius and turning angle, which particularly impact vehicle performance parameters like acceleration [15-16]. These factors lead to notable differences in driving behaviour compared to vehicles on standard planar roads. Vehicle acceleration is an indicator to evaluate flat curve designs' rationality, comfort and stability. In addition, the vehicle will show a unique spiral trajectory when driving on the spiral ramp, and the geometric linear characteristics of the spiral ramp determine the trajectory shape. The ramp's curve radius, turning angle and slope size affect the vehicle's trajectory, which means the driver must frequently adjust the speed to ensure the vehicle's longitudinal, lateral and vertical stability. Therefore, it is necessary to deeply analyse the driving behaviour characteristics of urban underground spiral ramps.

2. LITERATURE REVIEW

As car ownership and the number of drivers increase, the safety situation of road transportation worsens, with frequent traffic accidents and more challenging driving conditions, particularly in areas with wide roads and large city blocks, which often experience high traffic mortality rates [17-19]. Traffic accidents typically result from the synergistic imbalance between people, vehicles, roads and surrounding environmental factors [20]. For instance, aggressive driving significantly impacts fuel consumption and emissions while also compromising safety [21]. To reduce traffic accidents, many scholars have proposed improvements in traffic conditions through design, such as road height profile design [22]. However, in addition to these macro-level improvements, the operational characteristics of vehicles are also crucial for enhancing road traffic safety. Road alignment design must be based on the driver's behaviour and the vehicle's operational characteristics to better align road parameters with driving patterns.

Driving behaviour is primarily characterised by acceleration, deceleration and turning. Acceleration is the core parameter that describes the running performance of the vehicle, reflecting the vehicle's dynamic capabilities and directly affecting passenger safety and comfort. Longitudinal acceleration indicates a vehicle's longitudinal stability and comfort, lateral acceleration represents lateral safety and comfort on curved sections, and vertical acceleration measures vertical comfort and stability of the road. In recent years, domestic and foreign scholars have researched vehicle acceleration using different research methods.

In the driving simulation test, many studies have focused on predicting acceleration amplitude and have verified that the 85th percentile deceleration value of actual driver operations exceeds 0.85 m/s^2, while the 85th percentile acceleration value is lower [23]. Subsequently, a multiple linear regression model was developed to predict lateral acceleration under combined horizontal and vertical alignment conditions. Based on this model, the minimum horizontal curve radius for an uphill curve was determined to be 400 m [24].

Additionally, acceleration and acceleration variation were proposed as metrics to evaluate the comfort of road horizontal alignment. The findings indicated that larger curve radii resulted in lower acceleration disturbances, leading to improved safety and comfort [25]. In addition, many scholars have conducted in-depth discussions on the impact of different factors on driver behaviour. In the horizontal curve section, deceleration ends near the centre of the curve, while acceleration begins near the end. The longitudinal downhill has a significant positive effect on acceleration but does not significantly affect deceleration [26]. Factors such as curve radius, transition curves, visibility and road cross-section typically influence a driver's lateral acceleration and trajectory. Additionally, a driver's behaviour and perception of the curve directly impact road safety [27-28]. For example, when the curve radius is 100 metres or less, the proportion of high-risk events is nearly ten times higher than that of curves with a radius greater than 100 metres [29]. In mountainous highway sections, deceleration and acceleration positively correlate with the change of maximum curvature type and slope [30]. Furthermore, studies on adjacent upstream and downstream sections found that the 400 m maximum curvature of the downstream section was positively correlated with acceleration and deceleration. In comparison, the 400 m circular section proportion of the upstream section was positively correlated with deceleration and negatively correlated with acceleration [31].

In the field test, on-board equipment was used to collect the real vehicle test data on different road sections, and it was found that curve direction, radius and length affect acceleration [32]. Drivers exhibit more significant behavioural changes with higher deceleration rates, especially on small-radius curves. Additionally, at least 7% of the deceleration process occurs within the curve [33]. This demand for deceleration is closely related to driver comfort during cornering. To optimise the driving experience, scholars have assessed driving comfort in different axial directions and developed a longitudinal acceleration model based on visual perception, as well as a model describing the relationship between acceleration, curve radius and cornering dynamics [34-35]. Acceleration depends on the length of the departing tangent, while deceleration correlates highly with the length of the approaching tangent [36]. When driving on a flat curve section, lateral acceleration depends on the driver's perception of road geometry and lane changes [37]. When drivers drive continuously on different curves, their deceleration and speed adaptation persist into the curve section [38]. In addition, lateral acceleration at ramp entrances is influenced by the curve's geometric shape [39]. For example, the curvature and length of ramps affect lateral acceleration, particularly in skewed and semi-direct ramps [40], and drivers tend to exceed the ramp advisory speed under free-flow conditions [41]. Furthermore, longitudinal and lateral acceleration amplitudes were used to evaluate the comfort of passengers and identify safe and adventurous drivers [42].

The literature review reveals that existing studies primarily focus on interchange ramps, urban roads, highways and mountainous roads, with limited attention to urban underground spiral ramps. Existing research mainly focuses on the relationship between driving speed and curve alignment parameters, while the correlation between triaxial acceleration and curve alignment parameters remains insufficiently explored. Moreover, prior studies predominantly use single- or dual-axis acceleration measurements to quantify road driving comfort, limiting the ability to comprehensively evaluate the overall comfort level in urban underground spiral curve driving. Therefore, a real-vehicle driving test was conducted to collect vertical, horizontal and longitudinal acceleration data from a passenger car on the urban underground spiral ramp. The relationship between three-axis acceleration and curve alignment parameters was analysed and discussed. Three-axis acceleration was then selected as the evaluation index to assess overall driving comfort, providing a theoretical foundation for the alignment design and traffic operation management of urban underground spiral ramps. To achieve the objectives of this study, the following questions need to be addressed:

1) How do curves with varying radii affect vehicle safety and stability on urban underground spiral ramps?
2) How do curves with varying turning angles affect vehicle safety and stability on urban underground spiral ramps?
3) How do the effects of curves on urban underground spiral ramps differ from surface curves in terms of acceleration?

3. METHODOLOGY

The following sections outline the methods for analysing vehicle acceleration and curve alignment parameters. A summary of the relevant test design is provided, followed by an introduction to the testing procedures and data processing methods.

3.1 Test subjects

The experiment selected the Jiefangbei underground ring road test section – spiral ramp in Yuzhong District, Chongqing, China. The underground tunnel adopts a double-bore, single-track design with a speed limit of 30 km/h. It connects Jiabin Road and the underground ring road using straight segments and small-radius curves. It is divided into uphill and downhill ramps, consisting of circular curves with different radii. The spiral ramp curves were categorised and named in a specific sequence, with one curve (R = 40 m + 30 m) being continuous. The study area and surrounding road network are shown in *Figure 1*, the angle diagram in *Figure 2*, and the main technical indicators are listed in *Table 1*.

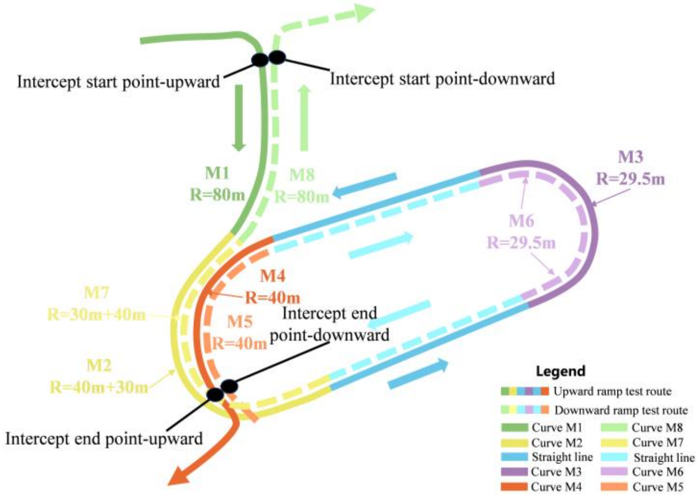


Figure 1 – Test roads in this study

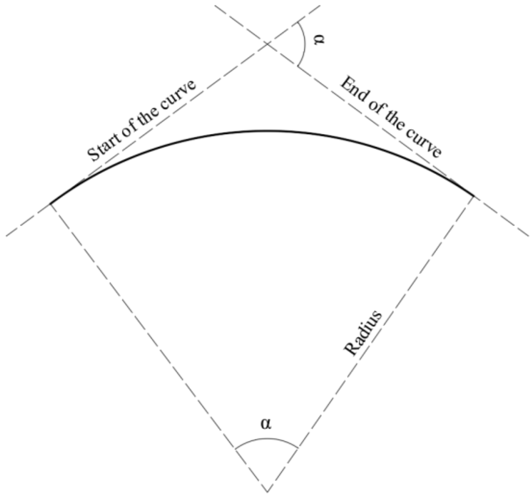


Figure 2 – Angle schematic diagram

Table 1 – Main technical parameters of the test roads

Ramp	Radius (m)	Angle (°)	Number	Design speed (km/h)	Superelevation (%)	Slope (%)	Minimum radius of vertical curve (m)
Upward ramp	80	38	M1	20	1.50	5.90	550
	40+30	149	M2	20	2.00	2.90	550
	29.5	175	M3	20	2.00	2.90	500
	40	102	M4	20	2.00	5.90	550
Downward ramp	40	102	M5	20	2.00	5.90	550
	29.5	175	M6	20	2.00	2.90	500
	40+30	149	M7	20	2.00	2.90	550
	80	38	M8	20	1.50	5.90	550

Note: 1. The longitudinal slope values of the upward/downward ramps are positive (upward) and negative (downward), respectively; 2. The minimum radius of concave/convex curves is 500 m/550 m, respectively.

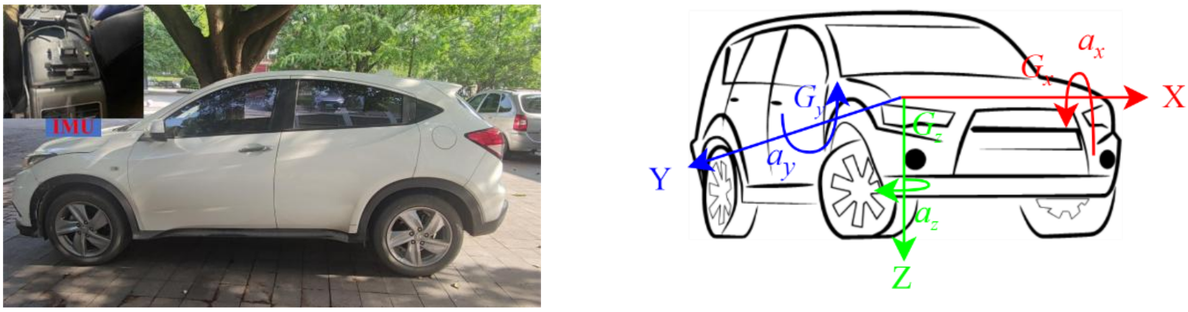
3.2 Test participants

A total of 20 skilled drivers participated in the experiment, comprising 14 males and 6 females, with an average driving experience of 13 years. The drivers' age distribution ranged from 20 to 50, with an average age of 39. Before the experiment, drivers were required to familiarise themselves with the vehicle's driving interface and conditions. Subsequently, each driver was asked to drive at a natural speed on the spiral ramp, maintaining their natural driving habits as much as possible during the experiment.

3.3 Test instruments and vehicles

The experiment used a micromechanical attitude and heading reference system (AHRS), also known as an inertial measurement unit (IMU), to collect three-axis acceleration and driving attitudes. The acquisition frequency of the IMU instrument is 10 Hz. A dashcam was employed to record the vehicle's trajectory, road conditions and any accident information in real-time during the driving process. The test vehicle selected was the Honda Vezel, a small to medium-sized SUV known for its excellent handling and stability. It represents

49% of the urban passenger car market, highlighting its prevalence on city roads. The test vehicle and instrument are shown in *Figure 3*. The test vehicle is primarily staffed with one driver and three recorders. The co-pilot recorder operates the vehicle terminal, while the two rear-seat recorders monitor sensor data and log the timestamps of feature points. These feature points mainly refer to the curve entry and exit points, facilitating subsequent data processing and analysis.



(a) *(b)*

Figure 3 – A figure with stacked subplots: a) Test vehicle and data collection instruments; b) Local coordinate system during vehicle driving

3.4 Experiment procedure and data processing

The experiments were conducted from 9:00 AM to 6:00 PM under sunny or cloudy conditions, avoiding the noon peak to reduce traffic interference. Before the test, the driving route was planned, and the appropriate data points were selected to capture the start/end locations and vehicle turning positions. Equipment adjustments were synchronised with the vehicle's operation at the start and end points to ensure data accuracy and reliability. Drivers then simulated natural driving conditions, completing 2 to 3 round-trip up and down the spiral ramp. The flow chart is shown in *Figure 4*. The aim was to eliminate random errors and collect sufficient data to analyse driver behaviour stability and trends during repeated driving.

Continuous driving data within the spiral ramp were extracted for each participant based on the data recording start/stop points. The data were then filtered and denoised using the smooth function in Origin software. The output continuous driving data included longitudinal acceleration a_x, lateral acceleration a_y and vertical acceleration a_z. The relationship between each parameter and vehicle driving is shown in *Figure 3(b)*, where G_x, G_y and G_z represent the body rotation angles around the three axes.

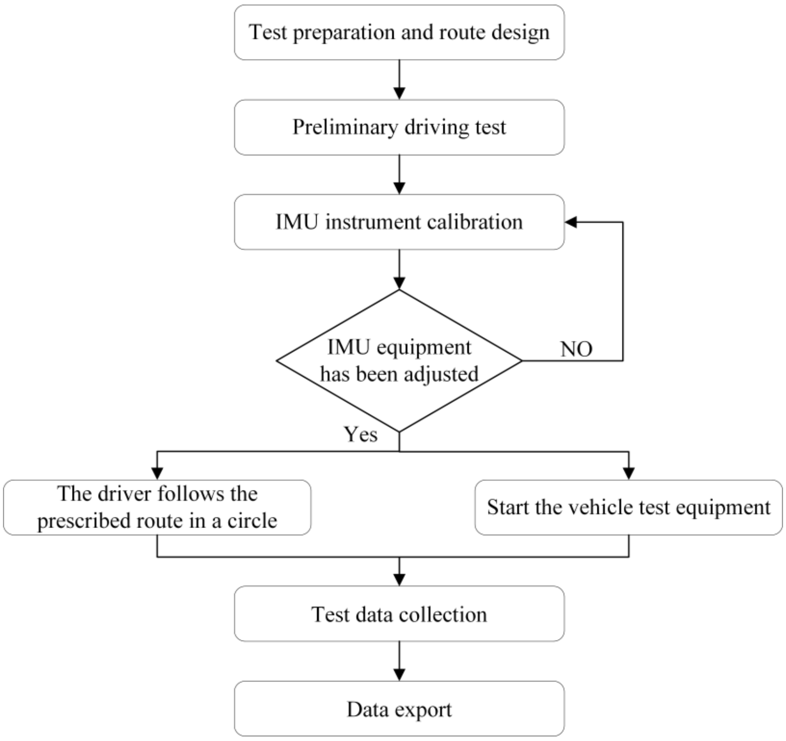


Figure 4 – Test flow

4. RESULTS

The geometric alignment of mountainous roads is complex and variable, characterised by frequent curves and slope sections. To adapt to the changing plane alignment curvature, drivers frequently use the brake, accelerator pedals and steering wheel to ensure driving speed does not exceed the critical safety speed of the flat curve, especially the small radius flat curve, and can maintain driving comfort. Additionally, uneven road surfaces and driving over vertical curves can cause fluctuations in vertical acceleration. Curve M3 in the upward direction of the spiral ramp is selected to demonstrate the extraction and pairing method for acceleration data. The data extraction method for the other curves follows the same procedure. *Figure 5* illustrates the vehicle speed in the upward direction.

As shown in *Figure 5*, vehicle speed changes when driving on a curved road section, causing acceleration fluctuations. These fluctuations will affect the vehicle's stability and handling, potentially increasing the driver's burden. Consequently, average acceleration values corresponding to various curve radii and angles of the spiral ramp were extracted based on the start and end points of different curves, and these values were organised into violin plots for detailed analysis. Additionally, the mean or peak values of the acceleration curve for each curve were extracted, paired with the curve radius/angle to form data points, and represented in scatter plots, as detailed below.

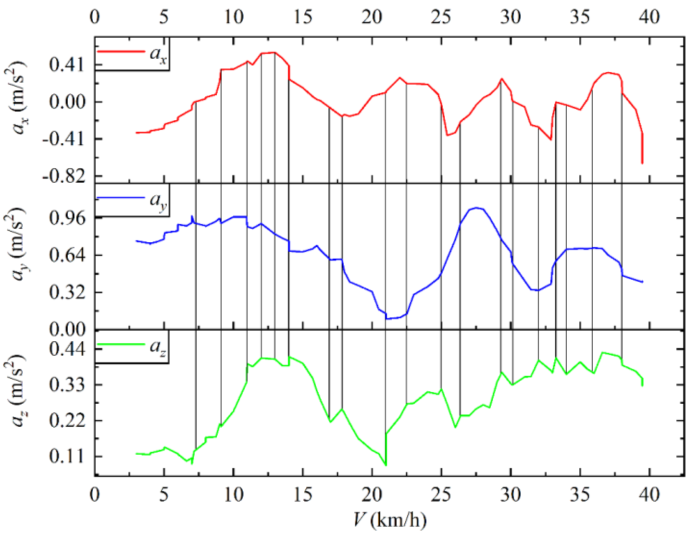


Figure 5 – Relationship between driving speed and three-axis acceleration (curve M3)

4.1 Sensitivity of longitudinal acceleration to curve geometric parameters

Significant speed fluctuations are experienced by drivers when driving on road sections with frequently changing geometric alignments. The exit acceleration a_x and entrance deceleration a_b are the main parameters describing the shape of the speed profile. Analysing the impact of various geometric parameters on exit acceleration and entrance deceleration helps identify potential safety hazards. It also enhances the scientific and rational design of curves.

Influence of curve radius on longitudinal acceleration

Vehicles tend to drift outward due to centrifugal force when driving on curves. To ensure lateral stability, drivers usually decelerate when entering a curve to enhance lateral controllability but will adopt an acceleration strategy when exiting the curve.

As shown in *Figure 6*, the entrance deceleration of upward ramp curves (M2, M3, M4) and downward ramp curves (M5, M6, M7) is negatively correlated with radius. However, the entrance deceleration amplitude within the 25%~75% range for curve M1 is significantly higher than that of the other upward curves, and the entrance deceleration variation range for curve M5 is significantly lower than that of the other downward curves.

Statistical analysis results for longitudinal acceleration are presented in *Table 2*. The data indicate that significant differences exist in the exit acceleration of upward and downward ramp curves with different radii (upward: $F(3, 83)= 10.763$, $p < 0.001$; downward: $F(3, 83)= 13.268$, $p < 0.001$), both positively correlated with radius. In other words, sharp turns (smaller radius of curvature) require the vehicle to slow down to maintain stability, while gentler curves (larger curvature) typically allow the vehicle to maintain speed or accelerate. The mean and standard deviation of exit acceleration for upward ramp curves are lower than those for downward ramps, indicating that vehicle acceleration remains relatively stable and consistent when navigating the upward ramp. In contrast, greater acceleration variations occur on downward ramps, reflecting more unstable acceleration behaviour. The average exit acceleration for the upward curve M1 (R = 80 m) is the highest at 0.66 m/s², while the lowest is observed in M2 (R = 40 m + 30 m) at 0.41 m/s². For the downward curve M8 (R = 80 m), the average exit acceleration reaches 1.28 m/s², the highest among all the curves, whereas M2 (R = 40 m + 30 m) exhibits the lowest value at 0.59 m/s².

Data presented in *Table 2* reveal significant differences in bending deceleration across different curves and driving directions (upward: F(3,83) = 17.672, $p < 0.001$; downward: F(3,83) = 33.272, $p < 0.001$). The average entry deceleration for the upward curve M1 (R = 80 m) is the highest at 0.88 m/s^2, while the downward continuous curve M7 (R = 40 m + 30 m) has the highest average entry deceleration at 1.46 m/s^2. It is also found that the mean and standard deviation of entrance deceleration for downward ramp curves (M5, M6, M7) are higher than those for upward ramps (M4, M3, M2), indicating a higher braking requirement for vehicles on downward ramps.

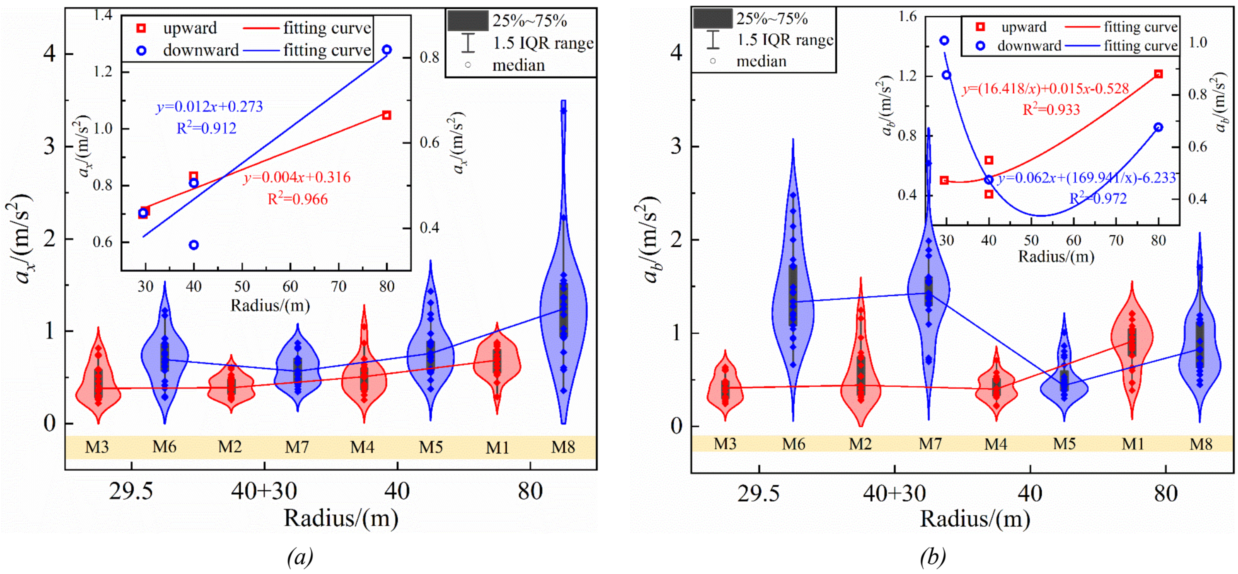


Figure 6 – A figure with stacked subplots: a) Relationship between exit acceleration and radius in spiral ramp curves; b) Relationship between entrance deceleration and radius in spiral ramp curves

Table 2 – One-way ANOVA results for longitudinal acceleration

Acceleration/ (m/s²)	**Angle/ °**	**Radius/ m**	**(1) Upward ramp**				**(2) Downward ramp**				**p-value (1)-(2)**
			Curves	**Mean (SD)**	**Parameter**	**p-value**	**Curves**	**Mean (SD)**	**Parameter**	**p-value**	
Exit acceleration	38	80	M1	0.66 (0.16)	F=10.763 p-value: ***	M1-M2 ***	M8	1.28 (0.64)	F=13.268 p-value: ***	M8-M7 ***	***
	149	40+30	M2	0.41 (0.11)		M1-M3 ***	M7	0.59 (0.16)		M8-M6 ***	***
	175	29.5	M3	0.43 (0.19)		M1-M4 *	M6	0.70 (0.25)		M8-M5 ***	***
	102	40	M4	0.52 (0.19)		M2-M3 0.957	M5	0.81 (0.28)		M7-M6 0.773	***
						M2-M4 0.106				M7-M5 0.255	
						M3-M4 0.283				M6-M5 0.806	

Acceleration/ (m/s^2)	**Angle/ °**	**Radius/ m**	**(1) Upward ramp**				**(2) Downward ramp**				**p-value (1)-(2)**
			Curves	**Mean (SD)**	**Parameter**	**p-value**	**Curves**	**Mean (SD)**	**Parameter**	**p-value**	
Entrance deceleration	38	80	M1	0.88 (0.25)	F=17.672 p-value: ***	M1-M2 ***	M8	0.86 (0.31)	F=33.272 p-value: ***	M8-M7 ***	0.747
	149	40+30	M2	0.55 (0.29)		M1-M3 ***	M7	1.46 (0.47)		M8-M6 ***	***
	175	29.5	M3	0.47 (0.20)		M1-M4 ***	M6	1.44 (0.49)		M8-M5 **	***
	102	40	M4	0.42 (0.12)		M2-M3 0.686	M5	0.51 (0.19)		M7-M6 0.877	0.061
						M2-M4 0.245				M7-M5 ***	
						M3-M4 0.867				M6-M5 ***	

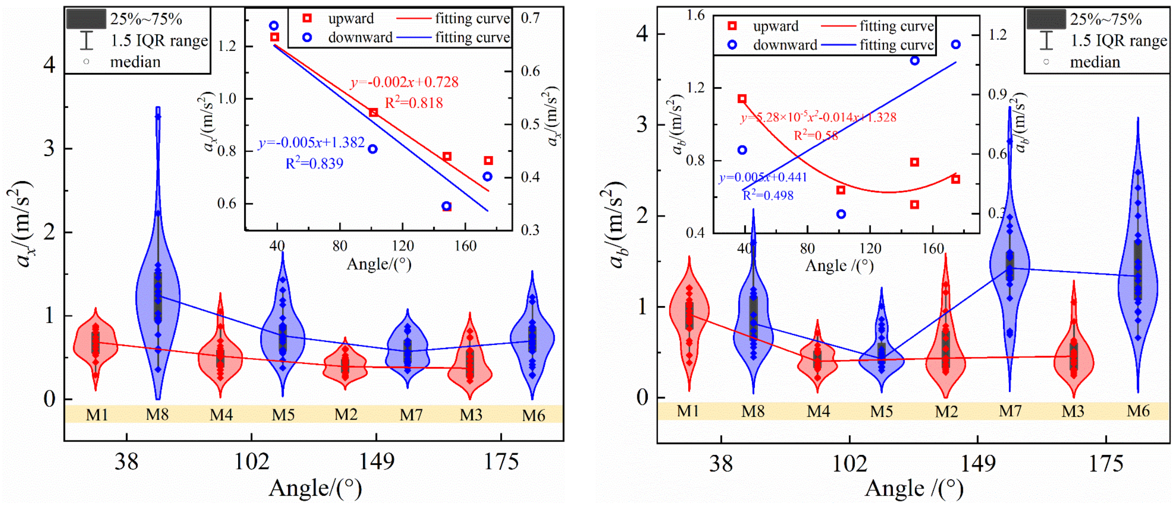
*Note: * represents $p < 0.05$, ** represents $p < 0.01$, *** represents $p < 0.001$(M8-M5:p=0.003); 'p-value(1)-(2)' represents the analysis results of the differences between upward and downward ramp curves.*

Influence of curve turning angle on longitudinal acceleration

The turning angle of a flat curve is another important parameter describing the geometric characteristics of curves. Different turning angles affect the driver's field of vision and steering difficulty differently, resulting in variations in driver behaviour and causing changes in acceleration.

Figure 7 reveals that the exit acceleration of the upward and downward ramp curves decreases as the turning angle increases. The smaller the turning angle, the more evident the driver's tendency to accelerate out of the curve. Additionally, the exit acceleration amplitude range for the downward curve with a 38° turning angle (M8) is significantly higher than that of the other curves.

According to *Table 2*, significant differences are observed in the entrance deceleration of upward and downward ramp curves under varying turning angles (upward: $F(3, 83) = 17.672$, $p < 0.001$; downward: $F(3, 83) = 33.272$, $p < 0.001$). The entrance deceleration of the upward ramp curves (M2, M3, M4) and downward ramp curves (M6, M7, M8) positively correlates with the turning angle. Sharp turns with larger angles force the vehicle to slow down for stability, whereas gentler curves with smaller angles allow it to maintain speed or accelerate. Furthermore, the average entrance deceleration for the upward large turning angle curves (M2, M3, M4) shows no significant pairwise differences ($p > 0.05$), and the same is true for the downward large turning angle curves (M6, M7). This indicates that when the curve radii are similar, the driver's deceleration behaviour remains consistent when entering these curves, highlighting the radius as a key factor in influencing speed control.



(a) *(b)*

Figure 7 – A figure with stacked subplots: a) Relationship between exit acceleration and turning angle in spiral ramp curves; b) Relationship between entrance deceleration and turning angle in spiral ramp curves

4.2 Sensitivity of lateral acceleration to curve geometric parameters

The extent and speed of the driver's steering wheel movements cause changes in lateral acceleration when driving on the frequently changing geometric road section, reflecting the vehicle's lateral stability and the driver's control behaviour. Analysing the impact of different curve geometric parameters on lateral acceleration assesses the vehicle's lateral safety when driving on curves, providing a theoretical basis for optimising curve design and enhancing overall comfort.

Influence of curve radius on lateral acceleration

Centrifugal force and lateral acceleration are generated when a car passes through a curve. Centrifugal force is an important factor influencing the driver's trajectory and speed choice behaviour.

In *Figure 8*, a clear trend shows that the lateral acceleration of the upward and downward ramp curves (M5, M6, M7) negatively correlates with radius. The average lateral acceleration of curves with a radius of 29.5 m (M3, M6) is significantly higher than that of curves with a radius of 80 m (M1, M8) ($p_{M3\text{-}M1} < 0.001$, $p_{M6\text{-}M8} < 0.05$), indicating that small-radius curves may affect vehicle driving stability more than ordinary-radius curves, leading to more noticeable driving discomfort and safety risks.

Presented in *Table 3*, the statistical analysis of lateral acceleration reveals that the lateral acceleration of the upward and downward ramp curves shows significant differences under different radii (upward: $F(3, 83) = 52.999$, $p < 0.001$; downward: $F(3, 83) = 22.671$, $p < 0.001$). The highest average lateral acceleration in the upward direction is observed at M3 ($R = 29.5$ m) at 1.85 m/s², while M1 ($R = 80$ m) has the lowest at 0.49 m/s². In the downward direction, M6 ($R = 29.5$ m) shows the highest average lateral acceleration at 1.30 m/s², and M5 ($R = 40$ m) is the lowest at 0.69 m/s². These findings suggest that when the actual driving speed is much higher than the design speed in the sharp curve section, it leads to higher lateral acceleration, requiring the driver to pay close attention, actively control the speed, and make significant steering corrections.

Moreover, the average lateral acceleration for the upward curves is significantly higher than for the downward curves (continuous curves $p < 0.01$, other curves $p < 0.001$). The lateral acceleration amplitude for the upward curves is below 3 m/s², while for the downward curves, it is below 2 m/s², indicating that drivers are relatively more stable when driving on downward curves. Moreover, within the upward ramp range, the average lateral acceleration for the left-turn curves (M2, M3, M4) is significantly higher than for the right-turn curve M1 ($p < 0.001$). In the downward ramp range, the average lateral acceleration for the left-turn curve M8 is lower than that for the right-turn curve M6 ($p < 0.05$), indicating differences in driving behaviour under varying turning conditions and reflecting the impact of uphill and downhill road conditions on lateral acceleration.

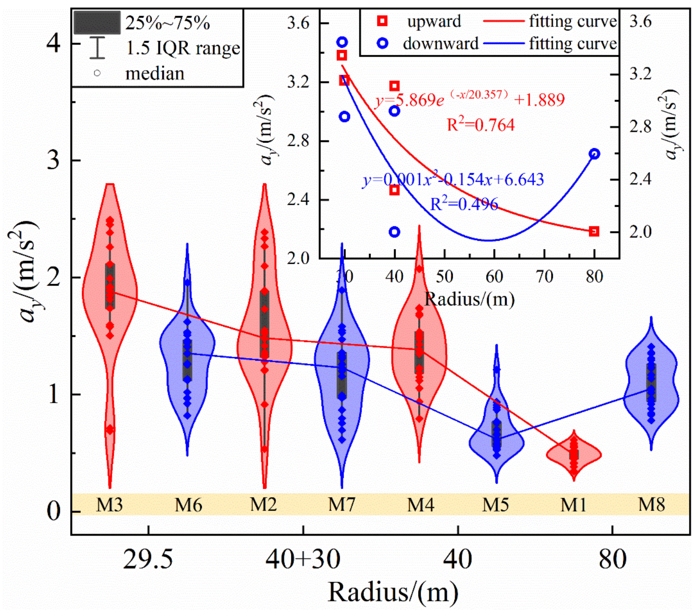


Figure 8 – Relationship between lateral acceleration and radius in spiral ramp curves

Table 3 – One-way ANOVA results for lateral acceleration

Angle/°	Radius/m	(1) Upward ramp				(2) Downward ramp				*p*-value (1)-(2)
		Curves	Mean(SD)	Parameter	*p*-value	Curves	Mean(SD)	Parameter	*p*-value	
38	80	M1	0.49(0.07)		M1-M2 ***	M8	1.09(0.19)		M8-M7 0.260	***
149	40+30	M2	1.55(0.47)	F=52.999 *p*-value: ***	M1-M3 ***	M7	1.18(0.33)	F=22.671 *p*-value: ***	M8-M6 *	**
175	29.5	M3	1.85(0.48)		M1-M4 ***	M6	1.30(0.28)		M8-M5 ***	***
102	40	M4	1.38(0.31)		M2-M3 0.686	M5	0.69(0.18)		M7-M6 0.138	***
					M2-M4 0.245				M7-M5 ***	
					M3-M4 0.867				M6-M5 ***	

*Note: * represents p < 0.05, ** represents p < 0.01, *** represents p < 0.001; 'p-value(1)-(2)' represents the analysis results of the differences between upward and downward ramp curves (M2-M7:p=0.006).*

Influence of curve turning angle on lateral acceleration

Drivers adopt different driving behaviours under different turning angle conditions. Differences in turning angles affect the driver's field of vision, the degree of steering difficulty and vehicle stability, causing changes in lateral acceleration.

Figure 9 reveals that the lateral acceleration of both the upward and downward ramp curves (M6, M7, M8) positively correlates with the turning angle. The average lateral acceleration for the curve with a turning angle of 102° (curve M5) is significantly lower than that of the other curves ($p < 0.001$).

Table 3 shows that the mean and standard deviation of lateral acceleration for the upward ramp curves (M2, M3, M4) are higher than those for the downward ramp curves (M7, M6, M5), while the opposite is true for the curves (M1, M8). Furthermore, the average lateral acceleration for the large turning angle curves (M3, M6) is significantly higher than that for the small ones (M1, M8) ($p < 0.05$, $p < 0.001$), affecting vehicle stability. Additionally, the average lateral acceleration for curve M3 is significantly higher than for curve M6 ($p < 0.001$), indicating that lateral acceleration amplitude is also influenced by slope under the same turning angle conditions.

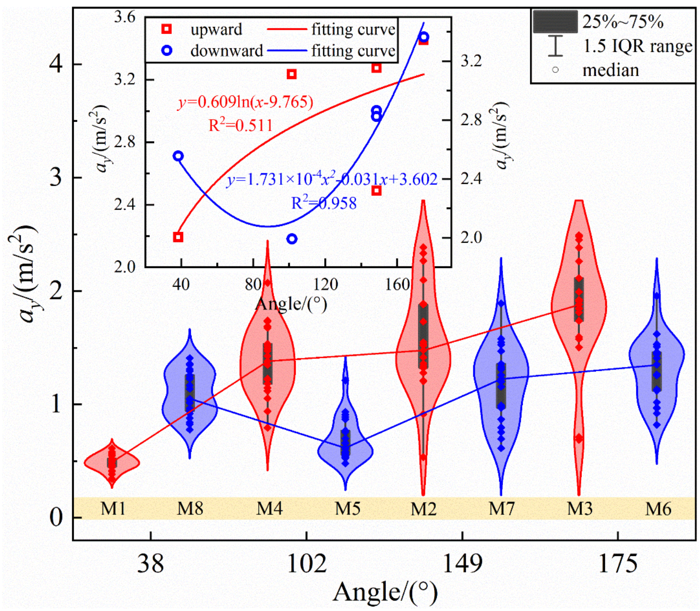


Figure 9 – Relationship between lateral acceleration and turning angle in spiral ramp curves

4.3 Sensitivity of vertical acceleration to curve geometric parameters

During curve driving, vehicles are affected by three-axis acceleration. Vertical acceleration fluctuates when vehicles pass through sections with significant road surface undulations and noticeable slope changes. Analysing the sensitivity of vertical acceleration to curve geometric parameters helps optimise curve and slope design, providing a reference for improving road surface comfort.

Influence of curve radius on vertical acceleration

The vehicle's trajectory differs significantly, affecting vertical acceleration when driving on continuous uphill or downhill sections with varying curve radii.

As shown in *Figure 10*, the vertical acceleration of the upward ramp curves increases with the radius, while the vertical acceleration of the downward ramp curves (M5, M6, M7) decreases with the radius. Furthermore, the vertical acceleration of the downward curves M6 and M7 is significantly higher than that of the upward curves M3 and M2, indicating that the upward direction provides a smoother driving experience compared to the downward direction.

The statistical analysis of vertical acceleration presented in *Table 4* reveals significant differences in vertical acceleration are observed between the on-ramp and off-ramp curves with different radii (upward: $F(3, 83) = 28.028$, $p < 0.001$; downward: $F(3, 83) = 13.428$, $p < 0.001$). The mean and standard deviation of vertical acceleration for the same radius in different directions also vary, likely due to factors such as the uphill/downhill design, vehicle speed and superelevation.

The highest average vertical acceleration in the upward direction is observed at M1 ($R = 80$ m), measuring 2.89 m/s². Curve M1's superelevation is lower than that of the other curves and is more influenced by the centrifugal force generated during the turn. As a result, the vehicle requires additional steering correction to maintain stability. This effect is especially noticeable when the driving speed significantly exceeds the design speed, as it may cause the vehicle's centre of gravity to shift, leading to instability. While the lowest is at M2 ($R = 40$ m + 30 m) in the continuous curve, at 1.26 m/s². In the downward direction, the highest average vertical acceleration is found at M2 ($R = 40$ m + 30 m), 2.79 m/s², and the lowest at M5 ($R = 40$ m), 1.63 m/s². These results suggest that the continuous small-radius curve has the greatest impact on the vehicle's vertical forces when driving downhill, which may increase instability and pose a higher safety risk.

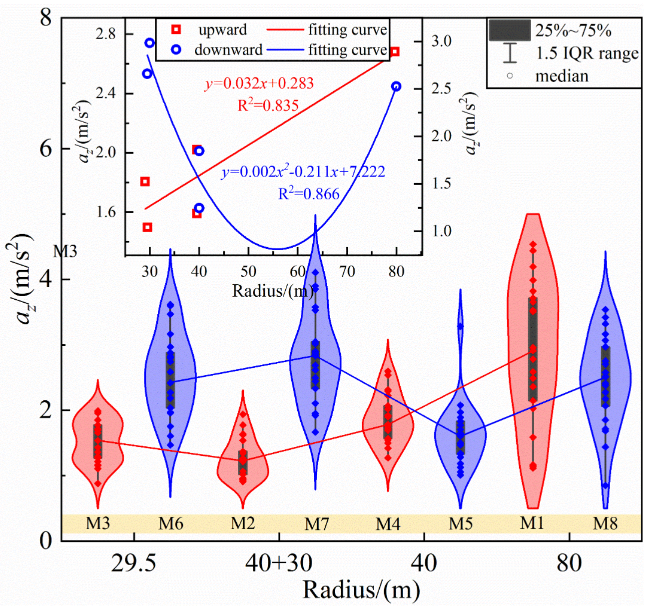


Figure 10 – Relationship between vertical acceleration and radius in spiral ramp curves

Table 4 – One-way ANOVA results for vertical acceleration

Angle/°	Radius/m	(1) Upward ramp				(2) Downward ramp				*p*-value (1)-(2)
		Curves	Mean(SD)	Parameter	*p*-value	Curves	Mean(SD)	Parameter	*p*-value	
38	80	M1	2.89(1.09)	F=28.028 *p*-value: ***	M1-M2 ***	M8	2.45(0.69)	F=13.428 *p*-value: ***	M8-M7 0.292	0.124
149	40+30	M2	1.26(0.30)		M1-M3 ***	M7	2.79(0.70)		M8-M6 0.972	***
175	29.5	M3	1.52(0.33)		M1-M4 ***	M6	2.53(0.62)		M8-M5 ***	***
102	40	M4	1.86(0.38)		M2-M3 0.522	M5	1.63(0.49)		M7-M6 0.539	0.089
					M2-M4 *				M7-M5 ***	
					M3-M4 0.295				M6-M5 ***	

*Note: * represents p < 0.05, ** represents p < 0.01, *** represents p < 0.001; 'p-value(1)-(2)' represents the analysis results of the differences between upward and downward ramp curves.*

Influence of curve turning angle on vertical acceleration

In continuous uphill or downhill sections, varying curve turning angles alter the vehicle's trajectory, affecting the vertical force on the vehicle and resulting in changes in vertical acceleration.

Figure 11 shows that the vertical acceleration of the upward ramp curves decreases with the increase in turning angle. Specifically, the vertical acceleration amplitude within the 25%~75% range for the curve with a turning angle of 149° (curve M2) is between 1 and 1.4 m/s², and the average vertical acceleration of M2 is significantly lower than that of M1 and M4 ($p_{M2\text{-}M1} < 0.001$, $p_{M2\text{-}M4} < 0.05$), which may be partly attributed to the greater superelevation design of M2 compared to M1. The higher superelevation design helps the vehicle reduce the effect of vertical force when passing the curve, thereby reducing the amplitude of vertical acceleration. Furthermore, the vertical acceleration of the downward ramp curves M5, M6 and M7 increases with increasing turning angle. However, the differences in average vertical acceleration between curves M6, M7 and M8 are insignificant ($p > 0.05$).

The mean and standard deviation of vertical acceleration for the upward ramp curves M1 and M4, with turning angles of 38° and 102°, are higher than those for the corresponding downward ramp curves M8 and M5, as shown in *Table 4*. However, the differences are not statistically significant ($p > 0.05$). The location of the curves at the start and end points of the test section and the endpoints of the test section are affected by the uphill and downhill sections.

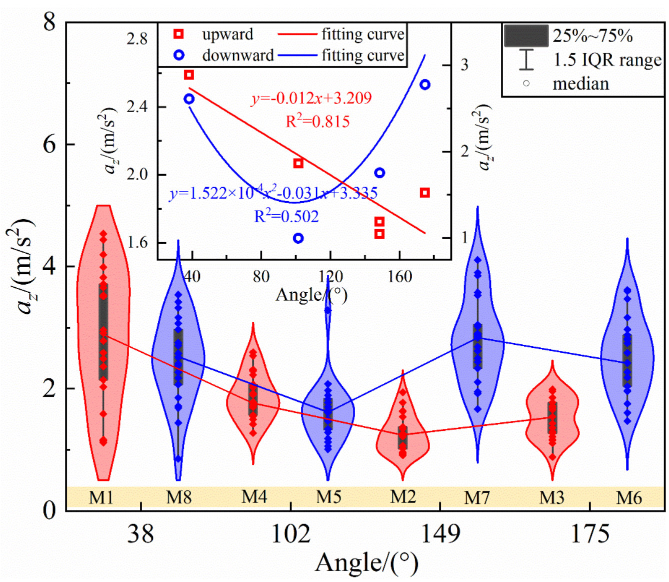


Figure 11 – Relationship between vertical acceleration and turning angle in spiral ramp curves

5. DISCUSSION

5.1 Correlation between longitudinal acceleration and curve geometric parameters

Regarding the relationship between acceleration (or deceleration) and curve radius and turning angle, a previous study [43] found that when driving on a curved road above ground, acceleration (or deceleration) decreases as the curve radius increases and increases as the curve angle becomes sharper. However, the research shows that the deceleration at the entrance of the underground spiral ramp is negatively correlated with the radius and positively correlated with the turning angle. Exit acceleration is positively correlated with the radius and negatively correlated with the curve angle. In other words, the deceleration trend at the entrance remains consistent, while the acceleration trend at the exit changes depending on the radius and angle of the curve. This difference may be due to the driver's perceived speed on the underground spiral ramp being lower than the vehicle's actual speed, leading to unintended speeding, especially the driver's vision and sight distance when driving on curves with ordinary radii, where good visibility and sight distance encourage drivers to accelerate, eager to exit the confined tunnel environment, resulting in a large amplitude of exit acceleration [23, 43]. In contrast, on large turning angle (or small radius) curves, drivers experience lower speeds within the curve and accelerate more slowly when exiting, resulting in smaller exit acceleration amplitudes. The deceleration amplitude for curve M5 is smaller than that for curve M8, possibly because curve M5, located at the starting point of the test route on a downhill section, sees cautious driving at lower speeds. Located at the endpoint, curve M8 experiences faster vehicle speeds; the gravitational force on the downhill facilitates acceleration, prompting more frequent braking and higher entrance deceleration amplitudes [43].

Furthermore, according to the longitudinal acceleration comfort evaluation index [44], the longitudinal acceleration (or deceleration) on the upward ramps was within the comfort thresholds. However, 14% of drivers' longitudinal acceleration data exceeded the comfort threshold (a_x > 1.25 m/s²) when travelling downward ramps, specifically on curves M5 and M8. Additionally, only 6% of drivers' longitudinal deceleration data exceeded the comfort threshold (a_b > 2 m/s²) when travelling on curves M6 and M7, where these curves exceeded the comfort threshold for longitudinal deceleration (a_b > 2 m/s²). Downward ramps impose higher braking demands on vehicles, as shown in *Figure 12*. Road design and management departments should consider the distinct characteristics of upward and downward ramps in tunnel curve design. Prioritising a larger radius of approximately 80 metres in the upward direction, combined with deceleration measures such as signage or road markers, can reduce acceleration. In the downward direction, avoiding small-radius and continuous curves is essential. Instead, the radius should be increased to between 40 and 80 metres. Additionally, incorporating a suitable speed bump can enhance driving comfort and safety. A flatter curve angle close to 38° may be more appropriate for upward sections. Large-angle curves should also be avoided, as increased angles elevate the driver's handling load; angles from 40° to 100° are preferable.

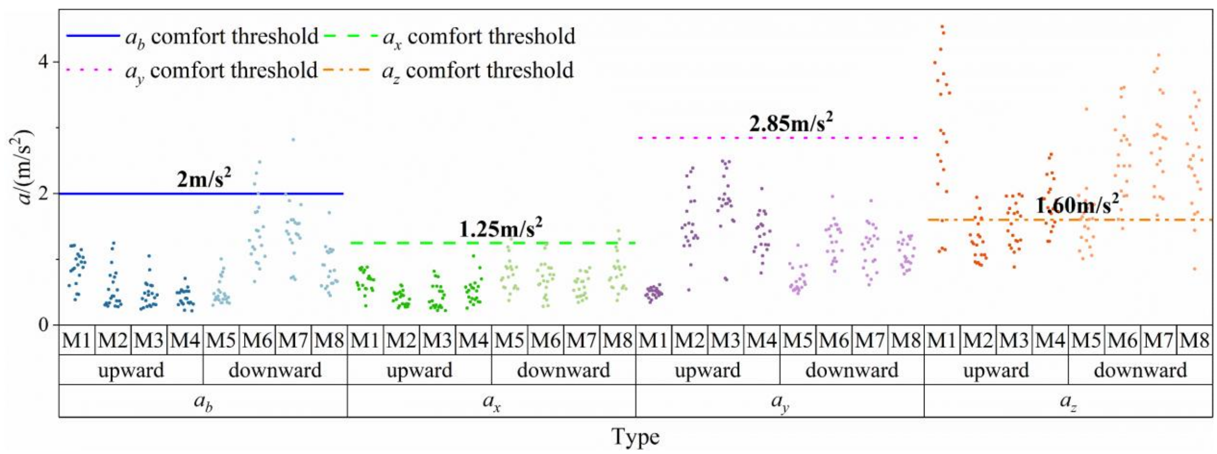


Figure 12 – Different types of acceleration distribution

5.2 Correlation between lateral acceleration and curve geometric parameters

Examining the relationship between lateral acceleration, curve radius and turning angle, previous studies show that the lateral acceleration amplitude on ground curves decreases as the curve radius increases [11, 45], while an increased turning angle increases it [46]. The study's findings on lateral acceleration changes with curve radius and turning angle are consistent with those of these studies. The phenomenon can be attributed to the enclosed environment of an underground spiral ramp, where lighting and ventilation conditions differ from those on ground roads, prompting drivers to adopt more cautious driving behaviour, for example, compared to an ordinary-radius (or small turning angle) curve, a small-radius (or large turning angle) curve reduces visibility, requiring the driver to adjust the vehicle's direction more frequently. Consequently, the frequency of steering wheel rotation increases, placing greater lateral force on the tyres [34]. As a result, small-radius (or large turning angle) curves have higher lateral acceleration amplitudes. However, the overall lateral acceleration amplitude for curve M8 is higher than for curve M5. Possibly due to the short transition curve connecting curve M8 and the preceding continuous curve M7. Influenced by the preceding continuous curve M7, acceleration out of the curve and into curve M8 occurs at a higher speed.

According to the lateral acceleration comfort evaluation index [35], the lateral acceleration data for both the upward and downward ramp curves remain within the comfort threshold (a_y < 2.85 m/s²), as shown in *Figure 12*. However, the driving comfort of the downward ramp with a small radius (or large turning angle) is higher than that of the corresponding upward ramp. The average lateral acceleration in both the upward and downward directions reached its maximum at the curve with a radius of 29.5 m (or angle 175°). Curves with ordinary radii (such as *R* = 80 m and *R* = 40 m) produce relatively low lateral acceleration. To reduce this low lateral acceleration and enhance driving comfort, the minimum curve radius should be at least 40 metres. Additionally, the average lateral acceleration values at curve angles of 38° and 102° are lower than those at a curve angle of 175°, suggesting that a flat curve angle design between 38° and 102° could be considered.

5.3 Correlation between vertical acceleration and curve geometric parameters

Vertical acceleration, a crucial indicator of vertical comfort and stability in road sections, is primarily caused by road surface unevenness and position changes when traversing vertical curves [47]. A previous study [48] found that vertical acceleration increases with road surface roughness amplitude, leading to discomfort for vehicle users. Additionally, curve radius and turning angle affect vertical acceleration when crossing curves. An increased curve radius usually results in a gentler turning angle, providing drivers with a broader field of view and higher speed, which increases vertical acceleration [49]. In the study, the trend of vertical acceleration with radius changes for upward ramps is consistent but differs for downward ramps. According to the vertical acceleration comfort evaluation index [35], 14.9% of the data remained below the vertical acceleration peak threshold (a_z < 1.6 m/s²) on the upward ramp, while 17.3% stayed below this threshold on the downward ramp, vertical acceleration exceeding the comfort threshold primarily occurs in the upward curves M1 and M4 and the downward curves M6, M7 and M8, as shown in *Figure 12*.

For example, the overall vertical acceleration amplitude of curve M8 is significantly higher than curve M5. According to design drawings, the vertical curve radius near curve M8 (800 m) is larger than near curve M5 (550 m). The weight reduction effect of the convex vertical curve results in smaller changes in vertical acceleration. Additionally, the superelevation design reduces lateral forces during curve traversal, thereby enhancing steering stability while driving. The superelevation of curve M8 is lower than that of the other curves; however, its vertical acceleration is higher. Furthermore, even with the same superelevation, the vertical acceleration of the curve changes due to the varying radius, as shown in *Figure 13*. Therefore, during road design, larger superelevation values and other alignment parameters should be considered to optimise driving comfort and safety.

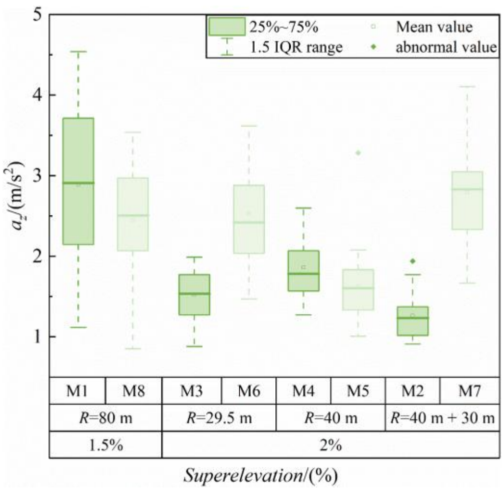


Figure 13 – Vertical acceleration and super high box diagram of the spiral ramp curve

In the upward direction, the continuous curve M2 exhibits the lowest vertical acceleration, suggesting that the length of the transition curve could be increased based on the actual terrain. Additionally, setting a speed limit sign within the curve can enhance driver comfort and safety. Another option is to increase the radius to approximately 40 m or design with a flatter curve angle near 102°. A curve radius of at least 40 m is recommended to mitigate instability and safety risks in the downward direction. Alternatively, a flatter curve angle near 102° could be used. Larger curve angles increase the likelihood that roadside objects may obstruct the driver's line of sight.

6. CONCLUSION

The study collected vehicle acceleration data through real vehicle tests under natural driving conditions, aiming to clarify passenger car driving behaviour characteristics on urban underground spiral ramps. It analysed the correlation between acceleration and curve geometric parameters, identifying the acceleration characteristics of passenger cars under various curve conditions. These findings provide a more scientific basis for traffic designers. The conclusions are as follows.

1) The exit acceleration of spiral ramp curves increases with the increase in curve radius and turning angle, while entrance deceleration shows the opposite trend. Entrance deceleration is negatively correlated with curve radius and positively correlated with turning angle. The driving comfort in the downward direction is lower than that in the upward direction, and the average exit acceleration and entry deceleration on the upward ramps are maximised at curves with a radius of 80 m and continuous curves, while in the downward direction, small-radius curves have a greater impact on speed reduction.
2) The lateral acceleration of spiral ramp curves decreases with increased curve radius. It increases with an increase in turning angle, with differences in the amplitude of lateral acceleration changes under different curve radii and turning angles. Driving comfort at the downward ramp's small radius (or large turning angle) curve was higher than that of the corresponding upward ramp curve.
3) The vertical acceleration of upward ramp curves is positively correlated with curve radius and negatively correlated with turning angle, while the vertical acceleration of downward ramp curves shows an opposite relationship. Ordinary-radius curves significantly influence vertical acceleration in uphill sections, while continuous small-radius curves have the greatest effect on vertical acceleration in downhill sections, increasing driving risk. Moreover, most drivers experience discomfort on either the upward or downward ramp.
4) The average exit acceleration of ordinary-radius (or small turning angle) curves is significantly higher than that of small-radius (or large turning angle) curves. Downward ramps place higher braking demands on vehicles, and the average lateral acceleration of small-radius (or large turning angle) curves is significantly higher than that of ordinary-radius (or small turning angle) curves. Additionally, the upward direction provides a smoother driving experience than the downward direction, and vertical acceleration is sensitive to road slope parameters. Therefore, in the actual tunnel curve design, the radius for the upward direction is set between 40 m and 80 m, with an appropriate flat curve angle (e.g. 38°). For the downward direction, the rotation angle should range from 40° to 100°, and the radius must be no less than 40 m.

The study analysed the driving behaviour characteristics of small passenger cars on urban underground spiral ramps. However, only the effects of curve radius, turning angle and longitudinal slope on vehicle acceleration were considered due to space limitations. In an actual tunnel operation environment, other factors such as vehicle type, tunnel lighting and lane width may also affect vehicle acceleration. For example, different types of vehicles may exhibit significant differences in acceleration and deceleration characteristics due to structural, weight and performance variations. Additionally, due to the small sample size of drivers, the representativeness of the experimental results may be affected. Future research should incorporate more experimental data and consider various factors comprehensively to better analyse the driving behaviour characteristics of passenger cars on urban underground spiral ramps.

ACKNOWLEDGEMENTS

The work was supported by the National Natural Science Foundation of China (No. 52202407), China Postdoctoral Science Foundation (No. 2022M710547) and Natural Science Foundation of Chongqing, China (CSTB2022NSCQ-BHX0731).

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