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Driving Characteristics and Speed Behaviour Parameters of Direct Traffic at Intersections Based on Field Driving Tests

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ABSTRACT

To reveal the speed control behaviour and manoeuvring characteristics of direct vehicles that stop-go through signalised intersections, a large-scale field driving test was carried out in Chongqing to collect vehicle data under natural driving conditions. The characteristics of speed, longitudinal acceleration rate and their two-dimensional correlation were analysed for deceleration and acceleration behaviour at signalised intersections. Further, a sensitivity analysis of the simulation model on measured data was done with the micro-traffic simulation experiment of a signalised intersection. The following were observed: (1) Drivers' speed-selection behaviours become more concentrated with closer distance from the stop point. The transects ±25 m from the stop point are abrupt change points in the discrete nature of driver speed-selective behaviours. (2) Drivers' desire to decelerate during the stop-go through signalised intersections is more robust, with the magnitude of pedal manoeuvres for deceleration behaviours being more intense than that for acceleration behaviours. (3) There is a nonlinear correlation between longitudinal acceleration rate and speed. The longitudinal acceleration rate increased with increase in speed and then decreased with the inflection point at 15 km/h. (4) The micro-traffic simulation's acceleration rate model is sensitive to measured acceleration rate parameters. This study guides the parameter setting of speed, deceleration rate and acceleration rate models for microscopic traffic simulation and for parameter calibration of the car-following model.

KEYWORDS

traffic engineering; signalised intersection; field driving test; speed characteristics; longitudinal acceleration rate characteristics; simulation verification.

1. INTRODUCTION

Intersections serve as crucial nodes and hubs in urban road networks, where flows of vehicles and pedestrians intersect and conflict with one another [1], leading to frequent traffic accidents and congestion. As bottlenecks in the road network, intersections directly affect not only the operational efficiency of urban road networks but also traffic safety. According to research, intersection traffic accidents account for 40% ~ 50% of total traffic accidents [2, 3]. To address these issues, urban road managers often install traffic signal control devices at intersections to control traffic flow in all directions, using the strategy of space allotment by time to ensure orderly passage. Vehicles inevitably need to decelerate, stop to wait, restart and accelerate to leave through signalised intersections.

The deceleration and acceleration driving behaviour at signalised intersections plays a crucial role in micro-traffic simulation [1], research of speed models [4, 5], car-following models [6], driving decision-making [7], fuel consumption models [8], emission models [9, 10], as well as intersection road geometry [11]. Therefore, studying driving behaviour characteristics at signalised intersections is of immense significance, as it can guide driving safety, reduce traffic conflicts, alleviate congestion and improve the operational efficiency of intersections.

2. LITERATURE REVIEW

Research on driving behaviour at signalised intersections has focused mainly on three aspects: single-vehicle driving behaviour [12], car-following modelling [6], and the influence of signal lights on driving decision-making [13].

2.1 Single-vehicle driving behaviour

Driving behaviour when manoeuvring a vehicle through an intersection is primarily reflected in speed changes [14] and drivers' physiological and psychological reactions [15]. Scholars have achieved numerous results using single-vehicle operating parameters to study driving behaviour characteristics at signalised intersections. Speed and longitudinal acceleration rate are the two most crucial indicators used to describe single-vehicle manoeuvring and micro-driving behaviour. Wortman & Fox [14] collected and analysed speed and deceleration rate data on vehicles decelerating at signalised intersections and found that the deceleration rate is related to the approach speed, with higher approach speeds resulting in greater deceleration rates. Wang et al. [16] confirmed that vehicles with higher approach speeds have longer deceleration times and distances and higher initial deceleration rates based on the onboard GPS data. Da Lio et al. [17] developed deceleration-stop behaviour models for intersections with different types based on parameters such as time, speed, deceleration rate and distance. Almallah et al. [18] analysed the correlation between start-up acceleration rates and response time for vehicles restarting after the signal turns green. Scanlon et al. [19] analysed the driving behaviour before the vehicle collision at intersections based on the acceleration data. Boonsiripant et al. [20] explored acceleration and deceleration zones of vehicles at intersections based on speed data. Bai et al. [21] analysed the influence of intersections with or without longitudinal deceleration lines on speed. Feng et al. [15] developed a model of correlation between maximum deceleration rate with heart rate change rate and pupil size of drivers.

2.2 Car-following modelling

Signalised intersections are zones where traffic flow is disrupted. The car-following behaviour in these zones differs significantly from that on normal roads [22]. In the research on car-following behaviour at intersections, Helbing & Tilch [23] proposed a generalised force model based on the speed difference between the front and rear vehicles that influences the rear vehicle. This model can avoid generating unrealistic acceleration rates in simulating vehicle motion delay, making it more in line with actual traffic situations. Aycin and Benekohal [24] used multiple simulation models to simulate single-vehicle-following behaviour separately and evaluated the results from various models. Zhao et al. [25] improved the full-speed difference model, one of the classical car-following models, by considering the aggregation and dissipation of vehicles at intersections. Zhang et al. [26] discovered that the signal state affected headway and developed a full-speed difference model at intersections considering different signal states.

2.3 Influence of traffic lights on driving decision-making

The existence of the dilemma zone is the primary cause of traffic accidents at intersections during signal phase switching [27]. Previous research has focused on the influence of the signal state on driving decision-making and the impact factors of driving in the dilemma zone. Koll et al. [28] analysed the differences in driver behaviour in stopping or not when the green light ends while with or without the flashing green. Long [29] analysed the differences in driver decision-making when stopping or passing through intersections under countdown or no countdown in the later stage of amber. Li et al. [30] developed a dynamic influencing factor model for the dilemma zone based on trajectory data at intersections, using parameters such as minimum perceived reaction time, maximum acceleration rate and deceleration rate. Papaioannou [31] and Rakha et al. [32] revealed the impact of age and individual differences on drivers' decision-making behaviour in the dilemma zone. Zhang et al. [33] utilised the structural equation model to study the impact of driver attributes, road conditions and the presence or absence of auxiliary driving systems on drivers' decision-making behaviour within the dilemma zone. The research by Majhi and Senathipathi [34] reveals a significant correlation between drivers' decision-making behaviour and surrounding vehicles during the amber phase. Wang et al. [35] developed a dangerous driving decision-making model, under the green flashing, based on acceleration rate and driver perception-reaction time. Chauhan et al. [36] developed a binary logistic regression model for driver decision-making behaviour at signalised intersections under disordered traffic by considering driving behaviour parameters and traffic infrastructure.

2.4 Summary

Overall, previous research on driving behaviour at intersections mainly focuses on vehicle driving characteristics [37], drivers' physiological and psychological characteristics [38] and car-following behaviour characteristics [39]. Among these, the research on vehicle driving characteristics at signalised intersections has always analysed the deceleration-stop or acceleration-depart behaviours individually when vehicles approach or depart [40]. More systematic research needs to be conducted on driving behaviour for the complete process of vehicle deceleration-stop-restart-acceleration-depart at intersections. Micro-traffic simulations of vehicles through signalised intersections require setting simulation parameters: speed, acceleration rate, deceleration rate and inter-vehicle distance [41]. Driving behaviour is influenced by the local environment and culture, with regional characteristics [11]. The simulation experiment parameter settings and data model establishment are based on real data as a reference. However, the studies on micro-traffic simulations and car-following models at signalised intersections in China lack the simulation model parameters compatible with the Chinese traffic environment. To obtain vehicle operation parameters at signalised intersections on Chinese urban roads, we recruited over one hundred drivers from the general populace to participate in a large-scale field driving test at signalised intersections. The recorded data are followed to analyse the statistical distribution characteristics of speed and longitudinal acceleration rate of vehicle stop-go straight through signalised intersections. The outcomes of this study assist in calibrating parameters for micro-traffic simulations and car-following models of signalised intersections in the Chinese traffic environment.

3. EXPERIMENT

3.1 Test location

Field driving tests were conducted on four urban roads in the main city zone of Chongqing to collect vehicle operation parameters under natural driving conditions. The test roads featured 15 signalised intersections of different types, including cross-shaped, T-shaped, Y-shaped, roundabouts and crosswalks. The first test road in Yuzhong District, Chongqing, featured 5 signalised intersections labelled a to e. The second and third test roads are located in Nan'an District, Chongqing, with the second featuring 3 signalised intersections labelled f to h, and the third has 4 signalised intersections labelled i to l. The fourth test road, in Yubei District, Chongqing, comprised 1 signalised intersection labelled m and 2 crosswalk signalised intersections labelled n to o. Vehicles passing through the signalised intersections of crosswalks need to stop-go when they encounter red lights or queues, with apparent deceleration and acceleration behaviours. Therefore, crosswalk signalised intersections were also included in the scope of the test roads. *Figure 1* displays panoramic views of selected signalised intersections, while *Table 1* presents each test signalised intersection's specific locations and primary characteristics.

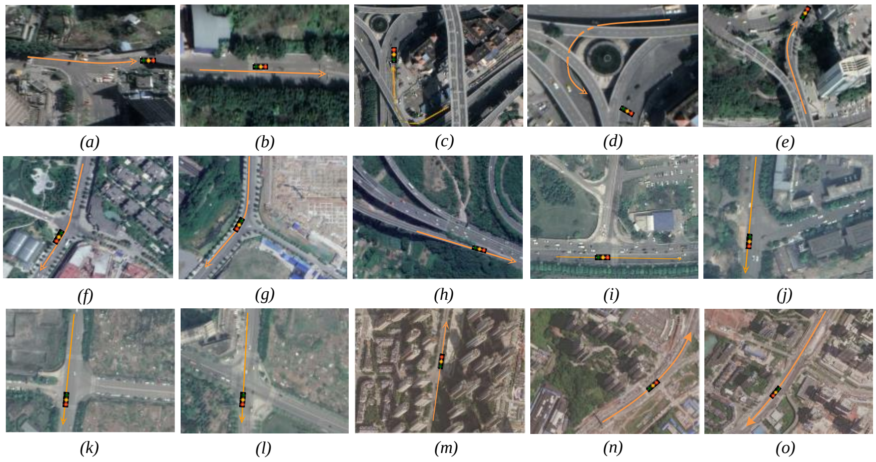


Figure 1 – Panoramic views of the test signalised intersections

Table 1 – Test signalised intersection information

Number	Test location	Types	Number of entrance lanes	Intersection angle [°]	Number of subjects
(a)	Zhongshan 3rd Road–Yangtze 1st Road Intersection	Y-shaped	5	60	
(b)	Changjiang Binjiang Road Crosswalk Signals	Crosswalk signal lamp	4	-	
(c)	Caiyuanba Interchange (No.1)	Roundabouts	2	-	30
(d)	Caiyuanba Interchange (No.2)	Roundabouts	4	-	
(e)	Zhongshan 3rd Road-Caiyuanba Bridge Intersection	Y-shaped	3	36	
(f)	Xianghuang Road-Dacheng Road Intersection	Cross-shaped	3	90	
(g)	Xianghuang Road-Old Factory Intersection	T-shaped	2	120	33
(h)	Xianghuang Road-Expressway Ramp Intersection	Y-shaped	2	15	
(i)	Yuma Road-Ewha Avenue Intersection	T-shaped	4	90	
(j)	Milan Road-Jinju Road Intersection	T-shaped	2	67	
(k)	Milan Road-Chuanghui Road Intersection	Cross-shaped	4	90	32
(l)	Milan Road-Yongning Road Intersection	Cross-shaped	3	75	
(m)	Yulu Avenue-Dingxiang Road Intersection	Cross-shaped	4	90	
(n)	Haier Road Pedestrian Crossing Light (No.1)	Crosswalk signal lamp	4	-	47
(o)	Haier Road Pedestrian Crossing Light (No.2)	Crosswalk signal lamp	4	-	

3.2 On-board equipment and test vehicles

The Mobileye 630 forward collision warning system gathered data on the distance between the front and rear vehicles, road curvature and lateral location. The Mobileye 630 device was connected to the car's CAN bus to acquire speed data, sampled at approximately 10 Hz. The SpeedBox gathered data on the vehicle's movement, including its trajectory, speed, longitudinal acceleration rate and location. The speed data output by Mobileye 630 was used to calculate the longitudinal acceleration rates with the differential calculation method. The calculation results were verified using the SpeedBox data. The signal noise and spikes from the real-time speed and longitudinal acceleration rate were removed with a moving average filter. Driving recorders were installed on the front windshield and right front car window to record the road environment, which assisted in filtering out invalid data in pre-processing. The Buick GL8 and the Hyundai Santa-Fe were chosen as the test vehicles, which cover the most common vehicle types found on urban roads. The test equipment and vehicles are shown in *Figure 2*.

(a) *(b)* *(c)*

Figure 2 – Test equipment and vehicles: a) Mobileye 630; b) speedbox; c) test vehicles

3.3 Subjects and field driving test process

A total of 142 drivers were recruited randomly from society to participate in the field driving test described in this paper. Subjects included drivers with different occupations and levels of driving experience: 105 male drivers and 37 female drivers. The age of the drivers ranged from 23 to 51 years, with an average age of 37 years. Their driving experience ranged from 2 to 31 years, averaging 11 years. Ethical guidelines were followed in all aspects of the study, following the approval of the Research Ethics Committee of the Chongqing Jiaotong University College of Traffic and Transportation. All subjects were informed of the potential accident risks and voluntarily signed an informed consent form before the test started. After the test ended, they all received 240 yuan RMB as compensation.

Before the test, the subjects were informed of the driving route but not the specific driving purpose to avoid influencing their driving behaviour. There was no intervention or prompt during the test, allowing the subjects to drive on the test route according to their usual driving habits. To collect as much driving data as possible on vehicles obstructed by red lights at intersections, each subject was asked to perform 2 to 3 tests along the predetermined route. The field driving test was conducted in four sessions, with the number of subjects per session as shown in *Table 1*.

4. SPEED BEHAVIOUR CHARACTERISTICS

When approaching a signalised intersection, the driver would apply the brake to decelerate and stop if there was a red light or queue. After the green light turned or the vehicles ahead moved, the driver would restart and accelerate. The passenger car cannot stop at the stop line every time because the front vehicle affects the actual stop point. Therefore, in this study, the speed control behaviours of passenger car stop-go through signalised intersections are divided into deceleration behaviour and acceleration behaviour according to the actual stop point. The actual stop point is identified based on the point where the speed curve value is 0. The peak points of the speed curve in front and behind the actual stop point are regarded as the start point of deceleration behaviour and the end point of acceleration behaviour, respectively. This zone is the data collection range of vehicles at signalised intersections, as shown in *Figure 3*.

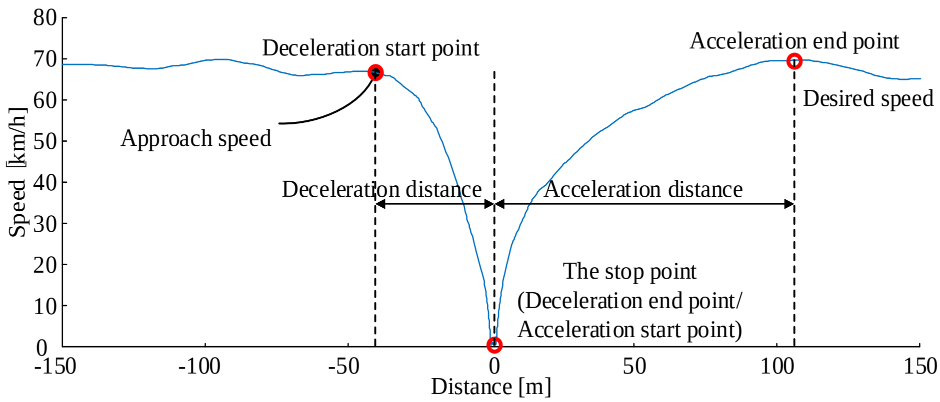


Figure 3 – Division of deceleration behaviour and acceleration behaviour

The deceleration behaviours of the vehicles approaching signalised intersections are divided into free-flow and following deceleration behaviour according to whether it is interfered with by the front vehicle. Similarly, the acceleration behaviours of the passenger car departing a signalised intersection are divided into with and without traffic conflict acceleration behaviour. When there is a large traffic flow in a signalised intersection zone, the vehicle's speed change is mainly affected by vehicles that overlap or intersect with its trajectory. The speed change of the vehicle without interference from other vehicles is strongly regular and primarily related to the driver's style and experience.

When vehicles approach signalised intersections, the instantaneous speed before sustained deceleration is defined as the approach speed for deceleration behaviour. When vehicles depart signalised intersections, the steady speed after the speed peak is defined as the desired speed for acceleration behaviour. The approach and desired speeds reflect the differences in the driving environment during vehicle deceleration and acceleration at signalised intersections. Drivers have different deceleration and acceleration behaviours under different approach speeds and desired speeds.

Vehicle driving data that are affected by trajectory conflicts are filtered out. The filtered acceleration behaviour and deceleration behaviour speed data are grouped and summarised according to the approach and desired speed at the same interval. Statistical analysis of the approach and desired speeds shows a wide and similar distribution ranging from 20 km/h to 90 km/h with a positively skewed distribution. Most of the approach and desired speeds fall between 20 km/h and 70 km/h, with only a few exceeding 70 km/h. The vehicle driving data of deceleration and acceleration behaviour have been grouped into 6 groups with a 10 km/h increment, as shown in *Table 2*.

Table 2 – Deceleration/acceleration trips distribution at different approach and desired speeds

Approach/desired speed [km/h]	Number of deceleration trips	Number of acceleration trips
20–30	53	71
30–40	68	111
40–50	139	100
50–60	120	97
60–70	66	40
>70	37	21
Total	483	440

4.1 Deceleration behaviour characteristics

Vehicle operating speed is a specific characterisation of driving behaviour. The 50th and 85th percentile speeds are important statistical parameters in driving behaviour studies and traffic facility design. To analyse the deceleration behaviour characteristics at different approach speeds, the speed curves of the same speed group and the 15th, 50th, and 85th percentiles are plotted in a coordinate system with the stop point as the origin, as shown in *Figure 4*. *Figure 4* shows a comparable slow decline followed by a fast decline in speed changes among various approach speed groups. Specifically, the passenger car decelerates slowly when it is far from the stop point and rapidly as it gets closer. Such manner of speed change suggests that drivers tend to accomplish their primary deceleration task when approaching signalised intersections. Furthermore, there is a comparable discrete nature regarding driver speed selection behaviour. When the passenger cars are far from the stop point, the speed values are more dispersed, indicating that the driver's speed-selection behaviours are more discrete and random. On the contrary, when the passenger cars are closer to the stop point, the speed values decrease rapidly while more concentrated, indicating that driver speed selection behaviours are less discrete and random. It is worth noting that the length of the deceleration distance increases with the value of the approach speed. For instance, the deceleration distance of the approach speed exceeding 60 km/h is over 200 m, and 70 km/h is over 300 m.

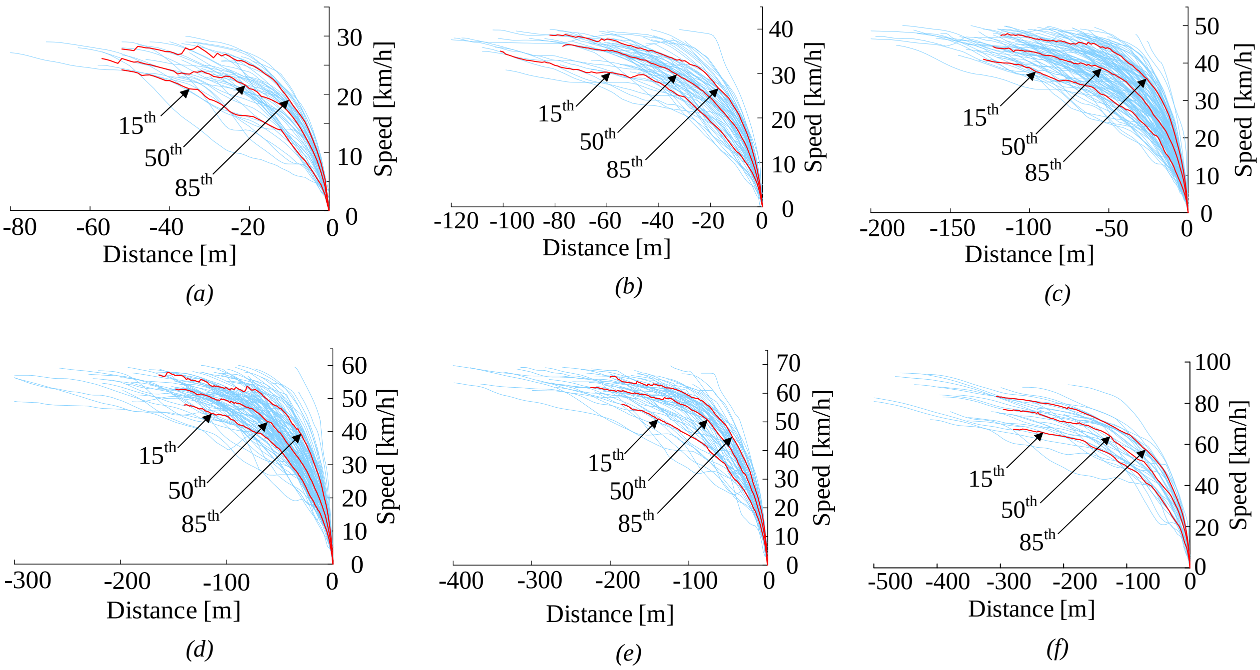


Figure 4 – Speed distribution curves of deceleration behaviour at different approach speeds: a) 20–30 km/h; b) 30–40 km/h; c) 40–50 km/h; d) 50–60 km/h; e) 60–70 km/h; f) above 70 km/h

4.2 Acceleration behaviour characteristics

The speed curves of passenger cars accelerating to depart signalised intersections are presented in *Figure 5*. As shown in *Figure 5*, the speed changes at different desired speeds are very similar and have some symmetry with the speed declines of corresponding approach speed groups. When accelerating away from signalised intersections, the speed increase of passenger cars is very rapid and steep for a very short period after restarting. Then, the speed increase gradually slows down until the desired speed is reached. Such manner of speed increase indicates that drivers strongly desire to accelerate after restarting and accomplish the main acceleration task within a very short distance from the stop point. Furthermore, the discrete nature of speed selection behaviours for acceleration when departing signalised intersections is similar and symmetrical to those for decelerating approaches. Specifically, within a very short distance after restarting, speed values increased rapidly while relatively concentrated, indicating that drivers' speed-selection behaviours converged strongly. On the contrary, it is more dispersed and random after speed values increase to be steady.

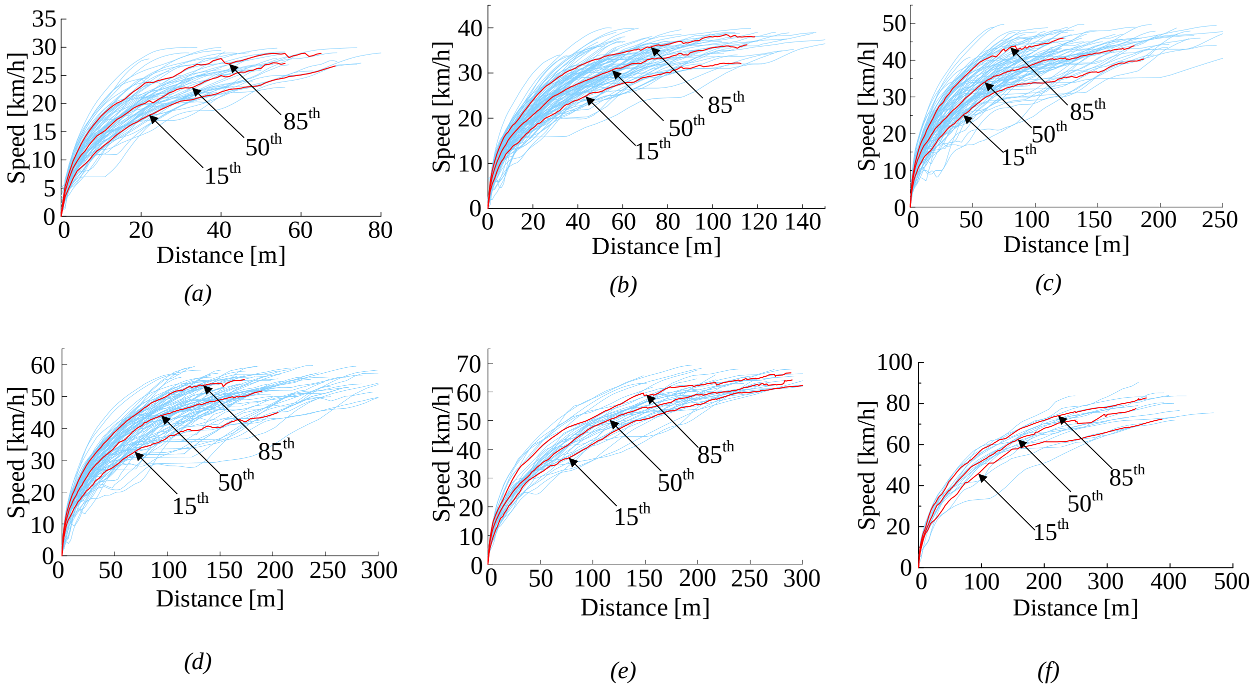


Figure 5 – Speed distribution curves of acceleration behaviour at different desired speeds:
a) 20–30 km/h; b) 30–40 km/h; c) 40-50 km/h; d) 50–60 km/h; e) 60–70 km/h; f) above 70 km/h

4.3 Discreteness of deceleration (acceleration) behaviour

To analyse the characteristics of drivers' speed-selection behaviours for passenger cars that stop-go straight through signalised intersections, the median speed curves within 300 m from the stop point under different approach and desired speed intervals are concentrated on the same coordinate, as shown in *Figure 6*. The median speed curves at the same approach and desired speed intervals are symmetrical. The median speed curves almost overlap near the stop point, and the median speeds of the same cross-section are practically equal. However, the median speed curves gradually separate as the distance from the stop point increases. It is related to the target speed of the deceleration and acceleration behaviours. The target speeds of deceleration behaviour are 0, i.e. the car is stopped. As passenger cars decelerate from various approach speeds to zero, drivers' speed selection behaviours converge with vehicles approaching the stop point. However, the target speeds for acceleration behaviour are drivers' respective desired speeds, which vary from driver to driver. Drivers' speed selection behaviours became discretely after passenger cars accelerate and drive a certain distance.

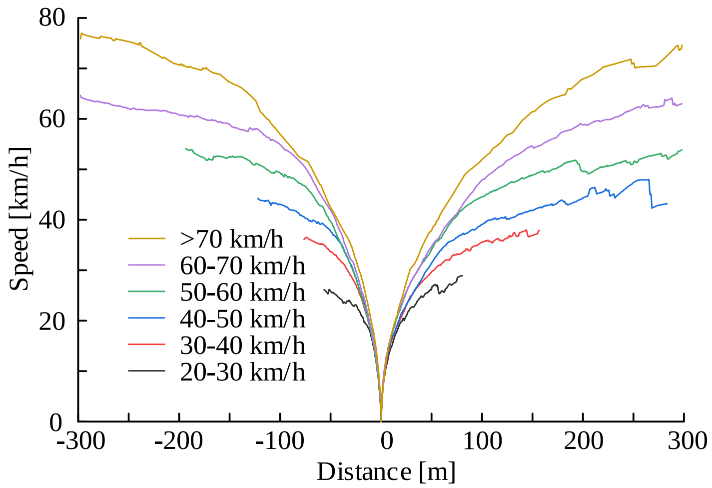


Figure 6 – Median speed curves for deceleration/acceleration behaviours

To further quantitatively analyse the discreteness of drivers' speed selection behaviour at signalised intersections, the 15th percentile (V15) and 85th percentile (V85) of all deceleration and acceleration curves were calculated. The speed amplitude width, 'V85-V15', represents the distribution width of speed data, i.e. the dispersion in speed selection behaviour among the middle 70% of drivers (as illustrated in *Figure 7*). The speed amplitude width at signalised intersections distributes within a narrow range of 15~25 km/h. During deceleration trips, the speed amplitude width gradually decreases before -25 m, followed by a sharp decrease between -25 m and 0. Conversely, during acceleration trips, the speed amplitude width sharply increases between 0 and 25 m, followed by a slow increase. Therefore, the 25th-meter cross-section in front of and behind the stop point is a critical point where the speed control behaviours change abruptly.

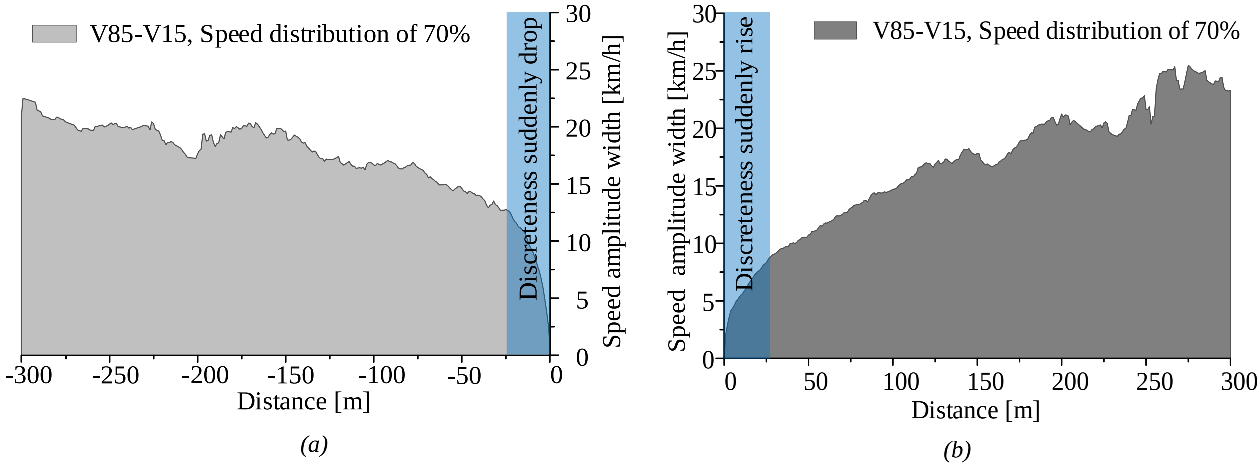


Figure 7 – Speed distribution at signalised intersections: a) deceleration behaviour; b) acceleration behaviour

5. LONGITUDINAL ACCELERATION RATE CHARACTERISTICS

5.1 Peak/average distribution characteristics

Longitudinal acceleration rates are the critical parameter describing deceleration and acceleration behaviours. The average and peak longitudinal acceleration rates directly reflect drivers' desire for deceleration/acceleration and aggressiveness in driving manoeuvres. The longitudinal acceleration rates are divided into brake-deceleration rate (a_b) and forward-acceleration rate (a_x) according to the threshold. The average deceleration and acceleration rates in each trip are calculated based on the formula $\bar{a} = \Delta v/\Delta t$ (Δv in the deceleration strip is the approach speed, and in acceleration trip is the desired speed). The peak deceleration and acceleration rates were defined from the maximum brake deceleration and forward acceleration rates, as shown in *Figure 8*.

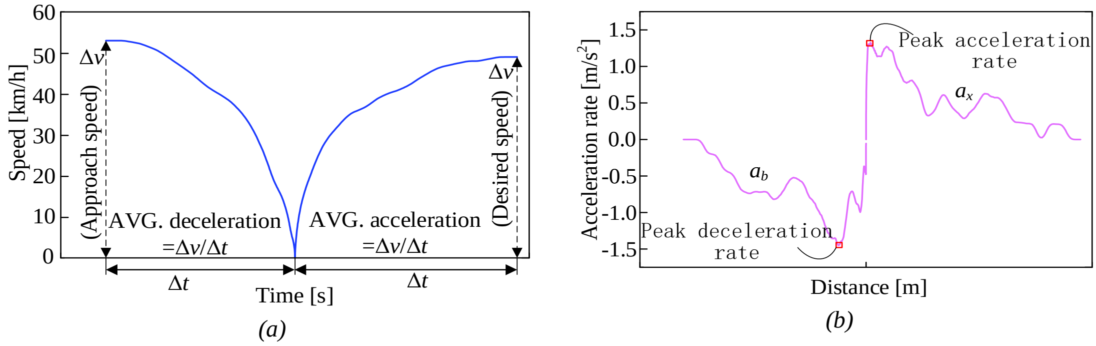
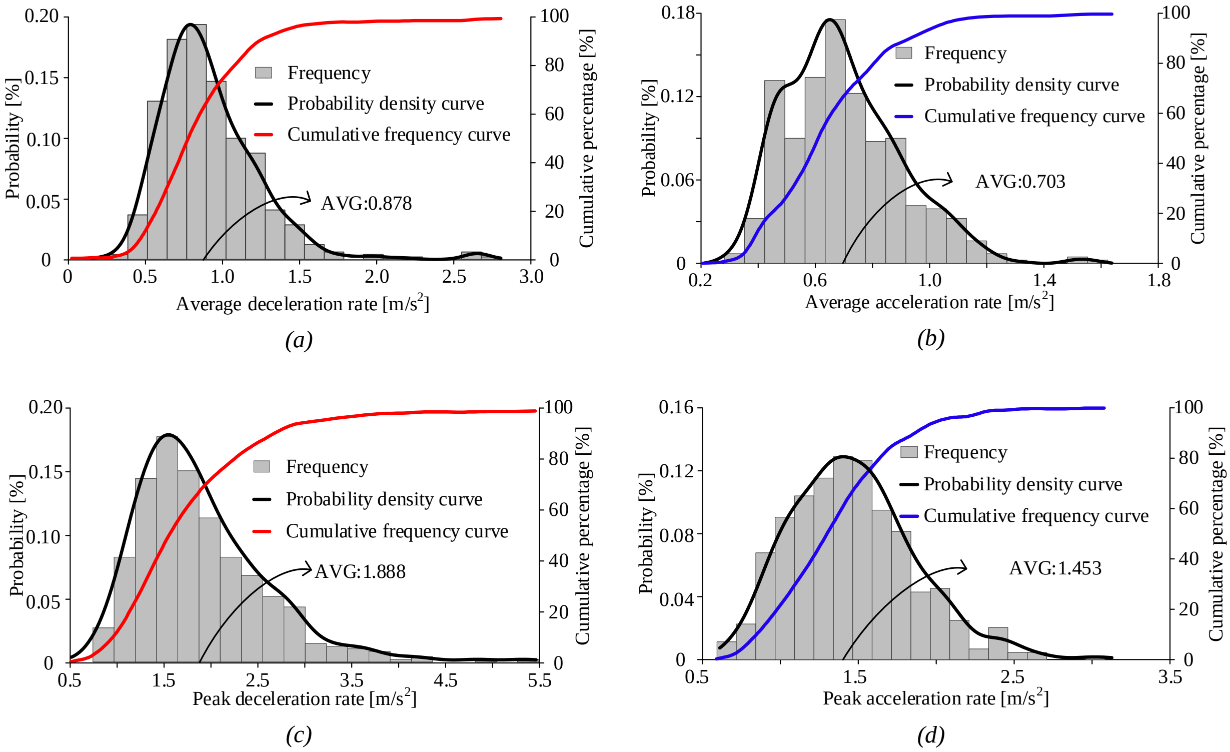


Figure 8 – Feature acceleration rate extraction diagram: a) average acceleration/deceleration rate; b) peak acceleration/deceleration rate

The obtained probability density and cumulative frequency curves for average deceleration rates, average acceleration rates, peak deceleration rates and peak acceleration rates were plotted within the same coordinate plot as shown in *Figure 9*. It can be observed from *Figure 9* that both deceleration and acceleration rates follow a left-skewed distribution. The probability density curves of average/peak deceleration and acceleration rates were fitted using a kernel density estimation method. The deceleration and acceleration rates at the peak of the probability density curves respond well to the drivers' deceleration and acceleration behaviour preferences. The preference value of the average deceleration rate is 0.8 m/s^2, of the peak deceleration rate 1.6 m/s^2, of the average acceleration rate 0.65 m/s^2 and of the peak acceleration rate 1.4 m/s^2, indicating that the preference values for the deceleration rate are significantly larger than that for the acceleration rate.

A comparison of the cumulative frequency curves of deceleration and acceleration rate shows that the average/peak deceleration rates are always greater than the average/peak acceleration rates at the same percentile. The differences between deceleration and acceleration rates (a_b-a_x) increase with the cumulative frequency, with the difference of the peak being greater than that of the average. For instance, the difference between the peaks at the 85th percentile is 0.968 m/s^2, which is greater than that of the average at the same percentile, which is 0.297 m/s^2. The comparison results of deceleration and acceleration rates indicate that drivers' desire to decelerate is more urgent than their desire to accelerate when the vehicles stop and go straight through signalised intersections; the manoeuvring of the brake pedal is more drastic than that of the accelerator pedal. In other words, drivers tend to complete the deceleration task in a shorter time when faced with a deceleration task and an acceleration task of the same magnitude.



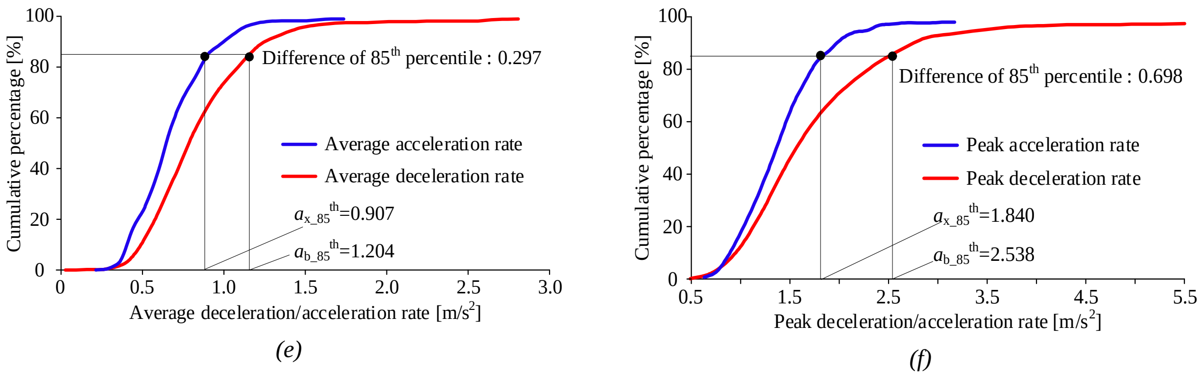


Figure 9 – Longitudinal acceleration rate probability distribution and cumulative frequency curve: a) average deceleration rate; b) average acceleration rate; c) peak deceleration rate; d) peak acceleration rate; e) average deceleration/acceleration rate cumulative frequency; f) peak deceleration/acceleration rate cumulative frequency

5.2 Time-varying characteristics

To analyse the vehicle's longitudinal acceleration rate dynamic characteristics during the deceleration and acceleration trips at signalised intersections, the curves of all deceleration rates and acceleration rates, and the 15th, 50th and 85th percentiles were plotted in two coordinate systems with the stop point as the origin, respectively. The absolute values of deceleration rates were taken to facilitate comparison with acceleration rates, as shown in *Figure 10*. It can be seen from *Figure 10* that the characteristic percentile deceleration rate curves rise slowly, followed by a rapid decline. According to the change characteristics of deceleration rate curves, the deceleration trip of the vehicle at the signalised intersection is divided into three stages: deceleration stage I, the accelerator pedal is released, causing the engine speed to drop, and the vehicle maintains a relatively stable lower deceleration rate for even deceleration due to the rotational resistance of the engine; deceleration stage II, the brake pedal is depressed, and brake pressure increases with brake pedal travel, resulting in a rapid decrease in speed; and deceleration stage III, the brake pedal is released, and the deceleration rate is reduced from peak to zero with the vehicle stopping.

The characteristic percentile acceleration rate curves rise rapidly, followed by a slow decline. Similarly, according to the change characteristics of acceleration rate curves, the acceleration trip of the vehicle at the signalised intersection is divided into three stages: acceleration stage I, the acceleration rate rises rapidly shortly after the restart because of a high acceleration reserve at low vehicle speeds and a strong desire to accelerate on the driver's part; acceleration stage II, the vehicle reaches a certain speed, and the acceleration rate starts to decrease continuously because the same force applied to the accelerator pedal after the gear is moved up does not allow a higher acceleration rate, resulting in the driver's desire to accelerate also decreasing; and acceleration stage III, the acceleration rate decreases to a stable value after the speed increases, and the vehicle accelerates uniformly until it reaches the desired speed.

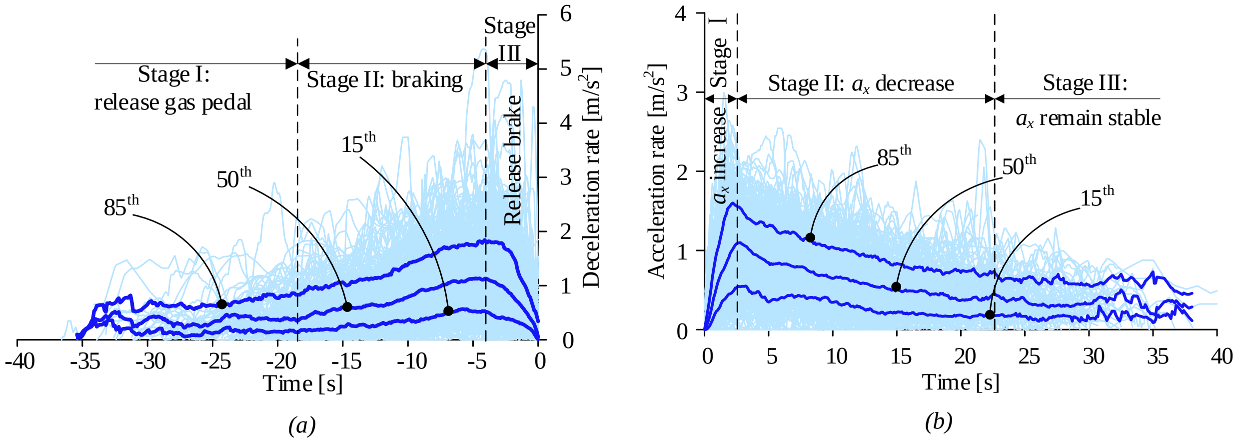


Figure 10 – Longitudinal acceleration rate time-varying characteristics; a) deceleration rate time-varying characteristics; b) acceleration rate time-varying characteristics

To clarify the effect of approach speed on the deceleration rate and of desired speed on the acceleration rate, the time-varying curves of median deceleration and acceleration rate under different groups were calculated and overlaid into two coordinate systems, respectively, as shown in *Figure 11*. It can be observed from *Figure 11* that both the deceleration time and the deceleration rate curve peak increase with the approach speed during the deceleration trip. During deceleration stage I, the deceleration rates under different groups were distributed at 0.2 ~ 0.5 m/s^2 with a relative concentration. During deceleration stage II, the brake pedal travel increased with approach speed, and the deceleration rate curves peaked and showed significant differences among groups, with the deceleration rate peaks distributed at 0.96 ~ 1.7 m/s^2. During deceleration stage III, the deceleration rate drops to 0 in less than 5 seconds.

It can also be seen in *Figure 11* that the acceleration rate curve peak increases with the desired speed during the acceleration trip. During acceleration stage I, the acceleration rate curves among groups overlapped almost wholly, and the acceleration rate changes were very concentrative. However, the acceleration rate curves appeared to be different when they reached their peaks, with the peaks distributed in the range of 0.9 ~ 1.2 m/s^2. This result indicated that the increase in the desired speed slightly boosted the desire for acceleration. However, when the desired speed reaches a high value, it no longer significantly affects the desire for acceleration. During acceleration stage II, the differences in the acceleration rate curves among groups became more pronounced, with it being high as the desired speed increased. During acceleration stage III, acceleration rates were concentrically distributed at 0.2 ~ 0.4 m/s^2.

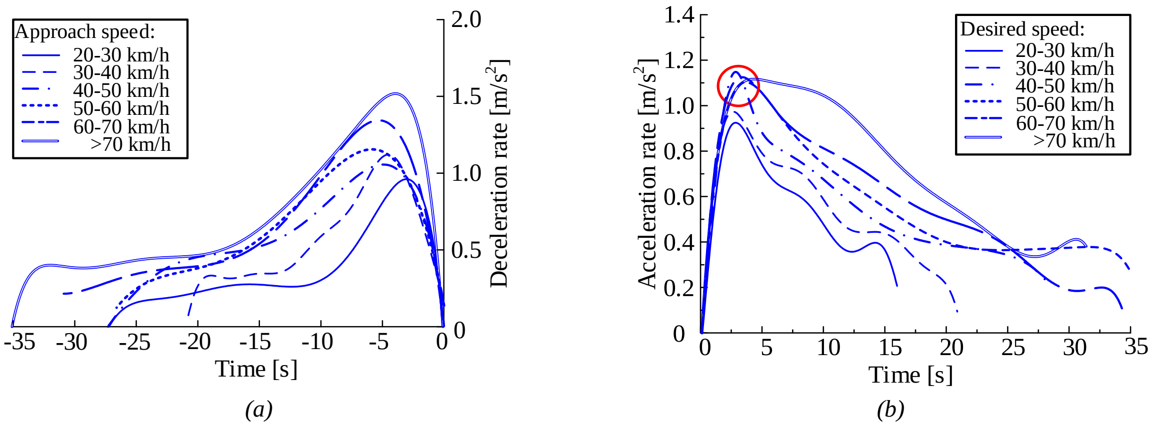


Figure 11 – Comparison of median deceleration/acceleration rates in different approach/desired speed intervals
a) deceleration rate; b) acceleration rate

6. DISCUSSION

6.1 Longitudinal acceleration rate distribution characteristics with speed

Researchers have been studying the correlation between speed and longitudinal acceleration rate in areas such as traffic simulation and autonomous driving. Data was collected on ‘longitudinal acceleration rate vs. speed’ from all subjects to analyse this correlation at signalised intersections, and a longitudinal acceleration rate distribution domain was obtained concerning speed. This distribution is shown in *Figure 12a*. The distribution shape stacked by all data in *Figure 12a* is conical. When the speed is low, the deceleration and acceleration rates increase with the increase in speed. However, when the speed is medium-high, the deceleration and acceleration rates decrease with increased speed. Also, the distribution width of the longitudinal acceleration rate gradually narrows. The relative density percentile contour lines of the data distributed domain were estimated by the kernel density method to determine the data distribution boundary. The upper and lower boundaries were fitted by a polynomial function, as shown in *Equation 1*:

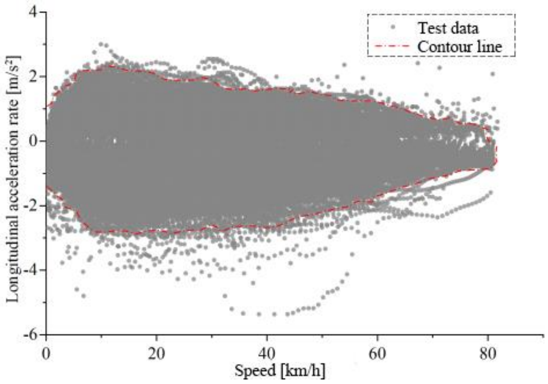
$$f(x) = P_1x^5 + P_2x^4 + P_3x^3 + P_4x^2 + P_5x^1 \quad (1)$$

where:

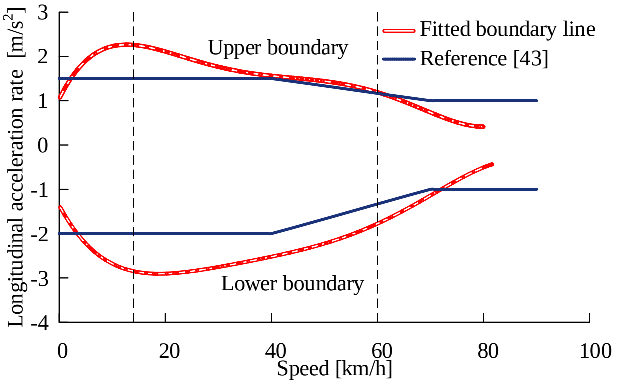
$f(x)$ – the acceleration/deceleration rate (m/s^2);

x – speed (km/h);

P_1~P_6 – the model coefficients whose values are shown in *Table 3*.



(a)



(b)

Figure 12 – The two-dimensional distribution of longitudinal acceleration rate with speed: a) distribution domain; b) distribution boundary line

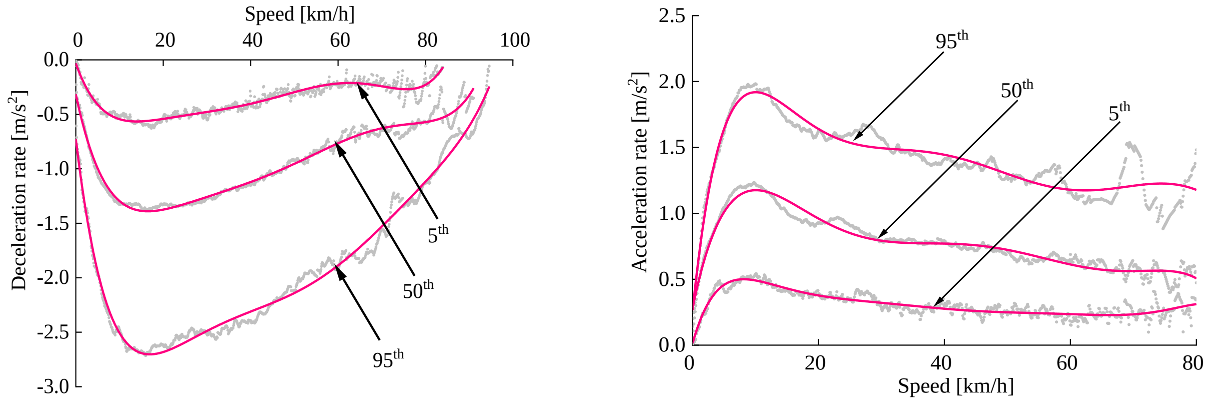
Table 3 – 'Longitudinal acceleration rate vs. speed' boundary model

Model coefficients and precision	**Deceleration rate – speed model**	**Acceleration rate – speed model**
P_1	-1.364E-08	2.36E-08
P_2	3.18E-06	-5.33E-06
P_3	-0.0002772	0.0004415
P_4	0.01179	-0.01641
P_5	-0.2253	0.244
P_6	-1.359	1.04
R^2	-1.364E-08	2.36E-08

The research in reference [42] indicates a linear negative correlation between acceleration rate and speed during the acceleration trip. Reference [43] categorised the speed into three ranges: low, medium and high, and provided the upper and lower boundary models for the distribution of longitudinal acceleration with speed. Specifically, when the speed is medium, the acceleration and deceleration rates change linearly; when the speed is low and high, the acceleration and deceleration rates remain constant. However, this study suggests a nonlinear correlation between longitudinal acceleration rate and speed, revealing the dynamic change characteristics of driving behaviour under different speeds. The upper and lower boundary lines fitted in this study and the boundary line models from the reference [43] are drawn in *Figure 12b*. It can be seen from *Figure 12b* that the upper and lower boundary lines are not strictly symmetrical, and the distribution threshold of the deceleration rate is overall higher than that of the acceleration rate. The speed as the independent variable in reference [43] was divided into three ranges: 0 ~ 40 km/h, 40 ~ 70 km/h, and > 70 km/h, to analyse the longitudinal acceleration rate change characteristics in each range. According to the change characteristics of boundary lines, the speed in this study was also divided into three ranges: 0 ~ 15 km/h, 15 ~ 60 km/h, and > 60 km/h.

When the speed is distributed at 0 ~ 15 km/h, the acceleration and deceleration rates of the boundary line increase with increasing speed and reach a peak near 15 km/h. When the speed is distributed at 15 ~ 60 km/h, the acceleration and deceleration rates of the boundary line gradually decrease as the speed increases. When the speed exceeds 60 km/h, the acceleration and deceleration rates of the boundary line have a significantly enhanced decrease due to the joint influence of the decreasing torque and the increasing air resistance after the vehicle reaches high speeds. Here, the three ranges of longitudinal acceleration rate changes with speed correspond to the three stages with time.

By interpolating the two-dimensional distribution of longitudinal acceleration rate and speed, the 5th, 50th and 95th percentiles of deceleration and acceleration rate with speed were calculated and curve-fitted, as shown in *Figure 13*, which can serve as references for the micro-traffic simulation parameters setting.



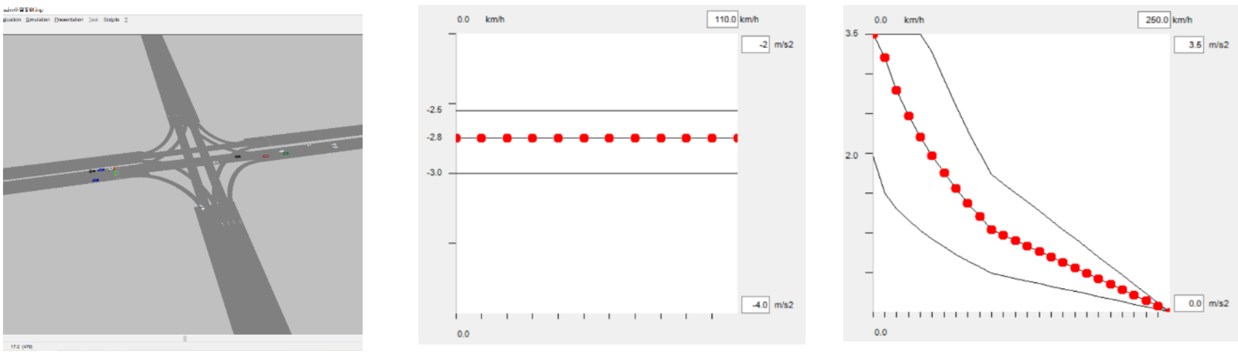
(a) *(b)*

Figure 13 – Longitudinal acceleration rate fitted curves vary with speed:
(a) deceleration rate fitted curves vary with speed; (b) acceleration rate fitted curves vary with speed.

6.2 Traffic operation simulation test at intersection

Currently, a widely adopted method for evaluating and improving intersection design depends on traffic simulation software for intersection modelling and simulation. Taking the micro-traffic simulation software VISSIM as an example, appropriate parameters must be set to control speed before performing simulations. Such parameters include desired speed, deceleration rate and acceleration rate, which depend on the real-vehicle test results. However, most Chinese research institutions and scholars currently use default values in the system or set parameters according to subjective feelings, which can lead to significant deviations between simulation results and actual observations. The real-vehicle test results in this study can provide a scientific basis for setting parameters and calibrating on intersection operation simulations.

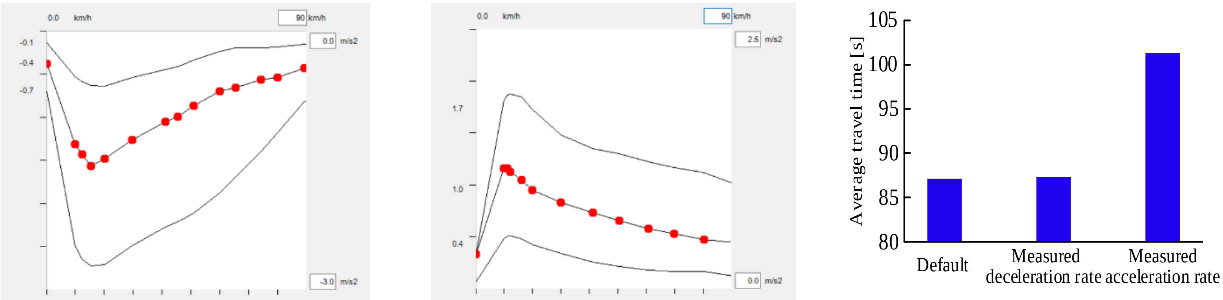
1) Simulation condition setting. The simulation, a straight passenger car stop-go through a signalised intersection, was conducted with VISSIM software to analyse and verify the importance of speed control parameter values. Two simulations were conducted, one utilising the software system's default values of acceleration and deceleration rate, while the other employed the real-vehicle test values from this study. A typical cross-shaped intersection was selected as the simulation road model, as shown in *Figure 14a*, with road geometry, signal timing and traffic volume data from reference [41]. The desired speed was to be set at 65 ~ 75 km/h. The desired acceleration and deceleration rate models were to be set up as speed control methods. The default deceleration and acceleration rates as functions of speed are shown in *Figures 14b* and *14c*, where the three curves represent the maximum, average and minimum deceleration and acceleration rates. It is apparent from *Figure 14b* that the default deceleration rate set in the VISSIM software system is a constant, i.e. the deceleration rate does not vary with speed, which is seriously inconsistent with the real-vehicle test value. The 5th, 50th, and 95th percentile curves of measured deceleration and acceleration rates versus speed were set to the adjusted desired deceleration and acceleration models' minimum, average and maximum values, respectively, as shown in *Figures 15a* and *15b*.



(a) *(b)* *(c)*

Figure 14 – Simulation intersections model and deceleration/acceleration rate default parameters in VISSIM:
a) road model; b) default desired deceleration rate; c) default desired acceleration rate

2) Simulation result analysis. The average travel time of the passenger car through the intersection detection section was chosen as the evaluation indicator for the simulation results. The simulation results of average travel time with default, measured deceleration rate and measured acceleration rate parameters are shown in *Figure 15c*. It can be seen from *Figure 15c* that the average travel time under the measured deceleration rate parameter is almost the same as that under the default parameter, and the average travel time under the measured acceleration rate parameter is longer than that under the default parameter. These simulation results show that the simulation model is more sensitive to acceleration rate than deceleration rate and that the acceleration trip of the passenger car departing the intersection under the default parameter is faster, i.e. shorter than that under the measured acceleration parameter, which suggests that the acceleration behaviour at the intersection under the default parameters is significantly distorted.



(a) (b) (c)

Figure 15 – Parameterisations of measured deceleration/acceleration and simulation results: a) adjusted desired deceleration rate; b) adjusted desired acceleration rate; c) simulation results

7. CONCLUSIONS

Vehicle operating parameters at signalised intersections in natural driving conditions were captured using real vehicle driving tests. Based on the time-varying characteristics of the longitudinal acceleration rate, the driving manoeuvring behaviours of straight passenger cars that stop-go through signalised intersections were analysed and divided into stages, i.e. manoeuvring patterns were identified. Longitudinal acceleration rate models with speed as the independent variable were developed based on the distribution characteristics of the 'longitudinal acceleration rate vs. speed' data. Intersection simulation tests were conducted in VISSIM to verify the importance of longitudinal acceleration rate values for the simulation results. The following conclusions were drawn.

1) Speed changes in deceleration and acceleration behaviours at different approach and desired speeds were similar and related to the distance of the stop point. The farther away from the stop point, the less pronounced the speed change magnitude, and the more discrete the speed distribution, the closer to the stop point, the more pronounced the speed change magnitude and the more concentrated the speed distribution. The transect 25m before/after the stop point is the abrupt change point at the discrete nature of the drivers' deceleration/acceleration behaviours.
2) The deceleration rate of straight passenger cars is significantly higher than the acceleration rate at signalised intersections. The preferred values of average and peak deceleration rates are 0.8 m/s^2 and 1.6 m/s^2, and the preferred values of average and peak acceleration rates are 0.65 m/s^2 and 1.5 m/s^2, respectively.
3) The deceleration behaviour can be divided in three stages based on the time-varying characteristics of the deceleration rate. During deceleration stage I, the vehicle experiences slight deceleration due to releasing the accelerator pedal and maintains a uniform deceleration rate. In deceleration stage II, the speed decreases rapidly due to increased brake force caused by pressing the brake pedal. Finally, during deceleration stage III, after the brake pedal is released, the speed decreases gradually until the vehicle comes to a complete stop at the target point.
4) The acceleration behaviour can be divided into three stages based on the time-varying characteristics of the acceleration rate. During acceleration stage I, the accelerator pedal is pressed along with the driver's strong desire to accelerate, and the acceleration rate rapidly peaks in 2~3 seconds. In acceleration stage II, the acceleration rate decreases slowly while the accelerator pedal travel is maintained. Finally, in acceleration stage III, the speed has reached a higher value, and the vehicle maintains a stable and low acceleration rate until the desired speed is reached.

5) The upper and lower boundary line models of the 'longitudinal acceleration rate vs. speed' distribution domain have been developed. These models reveal the nonlinear correlation between the longitudinal acceleration rate and speed. The models help calibrate the micro-traffic simulation's deceleration and acceleration rate, reducing the simulation results' distortion. Additionally, micro-traffic simulation experiments at signalised intersections were conducted in VISSIM to verify the sensitivity of simulation models to measured deceleration and acceleration rates.

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基于实车路试的交叉口直行车辆驾驶特性与速度行为参数

摘要：为得到车辆在信号交叉口直行时的速度控制行为和操纵特性，在重庆市开展了大规模实车驾驶试验，采集了自然驾驶条件下的车辆行驶数据，研究了信号交叉口加速/减速行为下的速度、纵向加速度特性以及两者之间的二维关系，接着开展了信号交叉口微观交通仿真试验，分析了仿真模型对实测数据的敏感性。结果表明：1)距离停驶点越近，驾驶人的速度选择行为越收敛，距离停驶点±25m 断面附近是速度选择行为离散性突变点；2)驾驶人在信号交叉口的减速意愿更迫切，减速行为中操作踏板的激烈程度高于加速行为；3）纵向加速度与速度之间呈非线性相关，随着速度增大，纵向加速度先增大后逐渐减小，速度 15km/h 为曲线变化拐点；4）微观交通仿真加/减速度模型对实测加速度参数具有显著敏感性。研究结论可对微观交通仿真的速度、加/减速度模型和跟驰模型参数值设定提供指导意义。

关键词：交通工程; 信号交叉口; 实车试验; 速度特性; 纵向加速度特性; 仿真验证