Traffic & Transportation

Asymmetric Behaviour and Traffic Flow Characteristics of Expressway Merging Area in China

Weihua ZHANG[1], Siping WEI[2], Changsheng WANG[3], Meng QIU[4]

Original Scientific Paper
Submitted: 15 June 2022
Accepted: 21 Nov. 2022

[1] weihuazhang@hfut.edu.cn, School of Automotive and Transportation Engineering, Hefei University of Technology

[2] 2021110973@mail.hfut.edu.cn, School of Automotive and Transportation Engineering, Hefei University of Technology

[3] wcshfut@163.com, School of Automotive and Transportation Engineering, Hefei University of Technology

[4] 1612370595@qq.com, School of Automotive and Transportation Engineering, Hefei University of Technology

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

ABSTRACT

Drivers show different characteristics in traffic oscillations. These differences reflect the driver's driving style, which is an important part of traffic uncertainty. This paper deeply explores the driving characteristics in asymmetric driving behaviour and its influence on traffic flow characteristics. The aim is to improve the understanding of safe driving. Continuous vehicle trajectories under various traffic flow conditions in an expressway merging area are obtained by aerial photography. Image processing technology is used to extract the basic parameters of traffic flow and vehicle operating characteristic data. Based on the measured data, the driver's response mode is subdivided into multiple sub-modes. On the basis of this study, the types and distribution of traffic hysteresis and the impact of asymmetric behaviour on merging area capacity are further revealed. The results show that the response coefficient will increase for 58.72 % drivers during the process of experiencing oscillation disturbance to rebalance. The traffic hysteresis caused by driver's asymmetric following behaviour in an expressway merging area is generally positive. This reduces the bottleneck outflow rate of the merging area by about 7 % on average. This study has important practical significance in analysing the formation mechanism of traffic congestion and adopting effective protective measures.

KEYWORDS

expressway; merging area; asymmetric behaviour; driver response mode; traffic hysteresis; capacity.

1. INTRODUCTION

The expressway merging area is a special section where the main road and the ramp intersect. It includes complex behaviours such as vehicle acceleration and deceleration, frequent lane changes and on-ramp traffic flow into the main line. This easily interferes with normal driving operations and can even lead to the instability of the main line traffic flow and frequent traffic accidents. Complex microscopic driver behaviour is an important factor in inducing traffic flow disorder in the merging area. Therefore, an in-depth study of microscopic behaviour in the expressway merging area is of great significance for improving the overall traffic efficiency of the expressway system.

Car-following behaviour is a basic micro-driving behaviour. It describes the interaction between two adjacent vehicles travelling in a queue in the same lane when traffic conditions are not suitable for overtaking [1]. When studying car-following behaviour, traffic flow researchers gradually observe asymmetric behaviour. Many scholars have studied the asymmetric characteristics of traffic following behaviour to explain the instability of microscopic traffic flow [2–5]. Car-following asymmetric behaviour refers to the behavioural differences between drivers in the process of acceleration and deceleration. Usually it is a phenomenon where the acceleration process is slow and the deceleration process is relatively rapid [6]. The study of asymmetric car-following behaviour is based on a comparative analysis of microscopic trajectory data from the Next Generation Simulation (NGSIM) data [7–8]. Vehicle running state data can be divided into different stages to explain asymmetric driving behaviour during acceleration and deceleration. It is pointed out that asymmetric driving behaviour research can help explain the causes of unstable traffic flow [9–10]. Chen et al. found that drivers' response characteristics changed before and after experiencing traffic oscillation by analysing the NGSIM vehicle trajectory. When the headway is large, most vehicles are in an accelerated state. At this time, acceleration changes slowly with the headway. When the headway is small, most vehicles are in a deceleration state, and acceleration changes rapidly with the headway. It is considered that headway is an important factor affecting the asymmetry of vehicle acceleration and deceleration [11]. Car-following vehicles show different characteristics in traffic, and this difference reflects driving style. It is an important part of traffic uncertainty. Although many scholars have studied the asymmetric characteristics, they are mainly based on NGSIM data. The understanding of the microscopic behaviour characteristics of moving vehicles in traffic is still limited, especially when it comes to the driver response modes adopted by different style drivers in traffic turbulences in expressway merging areas.

In the process of traffic oscillation formation and propagation, 'traffic hysteresis' often occurs. There are two explanations for traffic hysteresis. On the one hand, there is a delay in the recovery speed of traffic flow after external interference. On the other hand, the headway of the acceleration process is larger than that of the deceleration process at the same speed. Therefore, traffic hysteresis is considered to be caused by the asymmetry of acceleration and deceleration [12]. Newell first proposed traffic delays [13]. Yeo and Skabardonis analysed NGSIM trajectory data and verified Newell's speculation [14]. Traffic hysteresis may be due to the heterogeneity of driver characteristics and thus extends the Lighthill, Whitham and Richards (LWR) model. Assuming that each class follows a density-velocity relationship, a macro clockwise traffic hysteresis loop is generated through simulation. However, this is done mainly from macro speculation, rather than actual investigation to verify the conjecture [15]. Now traffic hysteresis is mainly measured by the speed-distance relationship of a single vehicle under traffic oscillation [16]. However, the study found that the existing theory of traffic hysteresis based on different driver acceleration and deceleration behaviour is incomplete. Drivers' reaction time and desired car-following distance have a great impact on traffic hysteresis and traffic flow characteristics [17–20]. Thus, it is necessary to consider different driving styles.

Due to the lack of measured data, most of the existing studies are based on NGSIM data for analysis. This leads to a lack of in-depth quantitative research on the impact of asymmetric driving behaviour on the stability and capacity of the merging area. Therefore, it is necessary to deeply explore the driving characteristics under asymmetric behaviour and its influence on traffic flow characteristics based on the measured data. This study has important practical significance in analysing the formation mechanism of traffic congestion and adopting effective protective measures. Firstly, continuous vehicle trajectory under various traffic flow conditions was obtained using aerial photography technology in Hefei, China. Image processing technology was used to extract the basic parameters of traffic flow and vehicle operating characteristic data. Then, the driver response modes were divided in more detail according to the basic parameters of each driver's response to traffic oscillation. Finally, the type and distribution of traffic hysteresis and the impact of asymmetric behaviour on merging area capacity was investigated. Further in this paper, Section 2 describes data extraction and research methods. In Section 3, the analysis results are given. A discussion is given in Section 4. Finally, the conclusion of this study is presented in Section 5.

2. METHODOLOGY

2.1 Instruments

The methodology is shown in *Figure 1*. According to the research purpose, it is necessary to obtain traffic flow data in various states. At the same time, the space-time continuity of vehicle trajectory has higher requirements. Video recording can be used to capture the whole process of traffic flow change. Therefore, high-altitude aerial photography is used to conduct traffic surveys. Data on static road structures and related geometric elements were collected, and dynamic traffic flow survey was conducted.

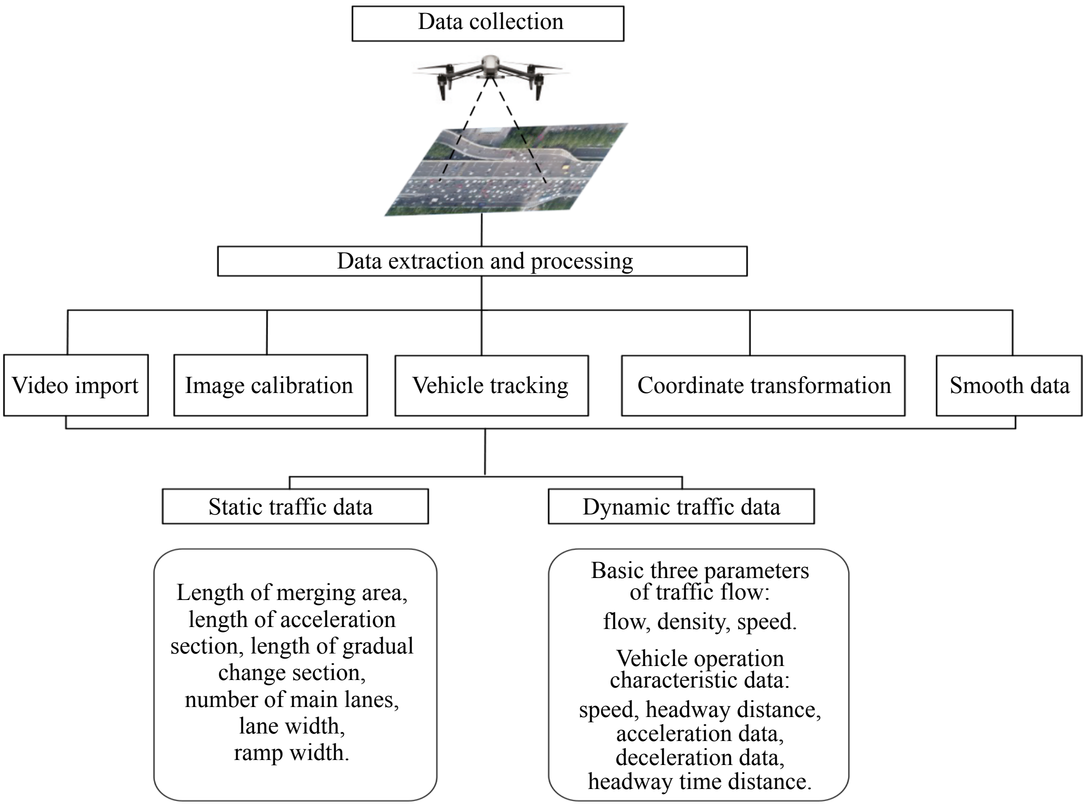

Figure 1 – Methodology scheme

2.2 Data acquisition procedures

Before officially starting the traffic survey, the time and place of the shooting needed to be determined. Jinzhai Road (It is a merging area from the south second ring road to the economic development zone.) in Hefei City was selected as the investigation area. Aerial photography technology was used to select multiple working days with good weather for video capture. Each video was edited to avoid instances of excessive jitter. The preliminary clear and stable video recording is shown in *Table 1*. After the shooting, the researchers measured and recorded the width, length and other data of the measured road section. The traffic direction of Jinzhai Road is from west to east. There is no other interference in the front and back of the merging area within 500 meters, which is helpful to study the natural variation of traffic flow before and after the merging area. The total length, acceleration length and gradual length of the study section are 290 m, 210 m and 40 m, respectively. The distance between the hard nose and the soft nose is 25 m, and the length of the actual merging area acceleration section is 185 m. Survey scenarios and geometric parameters are shown in *Figure 2*.

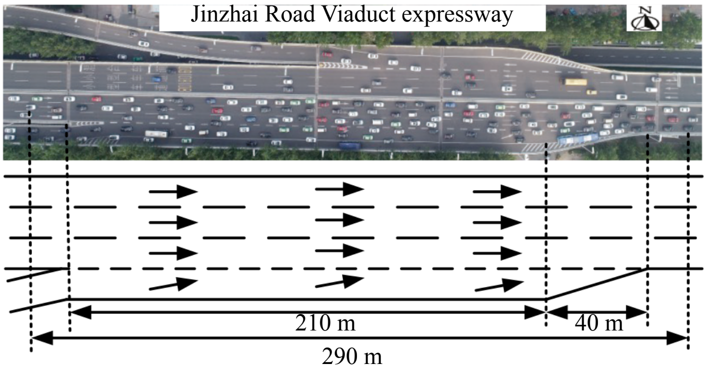

Figure 2 – Traffic survey scene

Table 1 – Aerial video recording

Working day flight time	Video shot duration [min]	Effective video duration [min]
7:23 a.m.–7:38 a.m.	15	12
7:18 a.m.–7:33 a.m.	15	11
15:45 p.m.–15:58 p.m.	13	9
15:32 p.m.–15:46 p.m.	14	10
17:26 p.m.–17:39 p.m.	13	10
17:35 p.m.–17:47 p.m.	12	9
17:25 p.m.–17:37 p.m.	12	6
17:33 p.m.–17:44 p.m.	11	5

2.3 Data extraction and processing

In order to ensure the effectiveness of car-following behaviour data, the preceding and following vehicles of the selected car-following samples in the extracted time series should be guaranteed uniqueness. The front car and the rear car do not change lanes and there are no other vehicles between the two cars. 235 pairs of car-following trajectories that meet the requirements were screened out. The extraction process is mainly divided into the following five steps. The specific extraction process and scenes are shown in *Figures 1 and 3.*

Step one: Video import. The aerial video is converted into the corresponding readable format and imported into the SIMI Motion video tracking software [21].

Step two: Image calibration. According to the measured distance, the pixel distance in the image is calibrated by four-point calibration method. Labels 1, 2, 3 and 4 are selected as four markers. The actual distances of 1–2 and 2–3 are obtained according to the manual measurement, so as to complete the image calibration, as shown in *Figure 3*.

Step three: Vehicle tracking. Manual dotting is used to mark the centre point of a vehicle as a tracking mark point. If the mark point is separated from the vehicle in the process of automatic software follow-up, it is necessary to interrupt and re-mark it from the current moment and then continue tracking until the marker disappears from the video. The tracking results are saved after tracking. This is equivalent to the coordinate position (x_0,y_0) of each frame of each vehicle relative to the origin of the initial coordinate.

Step four: Coordinate transformation. Video shooting and editing was done with the initial removal of larger jitter fragments, but the certain angle jitter still exists in the videos. In order to obtain accurate vehicle trajectory, the initial coordinates obtained by the third step tracking are projected along the lane line and the vertical lane line in each frame to construct a dynamic coordinate system XOY. In the coordinate system, the direction along the lane line is X axis, and the direction perpendicular to the lane line is Y axis. In order to facilitate the establishment of a dynamic coordinate system, three fixed points – A, B and C – are selected in the video tracking process to make $AB \perp AC$, as shown in *Figure 3*. The coordinates are (x_1,y_1), (x_2,y_2), (x_3,y_3). After coordinate transformation, as shown in *Formula 1*, the new coordinates of the vehicle at the current moment are (x_0',y_0').

Step five: Smooth data. Due to the influence of random factors in the tracking process, there are some random fluctuations in the space-time coordinates of vehicles. The 5-point moving average method is used to deal with the vehicle trajectory, as shown in *Formula 2*. After obtaining the coordinate information of the vehicle, the first derivative and second derivative of the coordinate will give the speed and acceleration of each vehicle at each moment.

$$\begin{cases} x_0' = \dfrac{\dfrac{y_2-y_1}{x_2-x_1}(x_1-x_0)+y_0-y_1}{\sqrt{1+\left(\dfrac{y_2-y_1}{x_2-x_1}\right)^2}} \\ y_0' = \dfrac{\dfrac{y_3-y_1}{x_3-x_1}(x_1-x_0)+y_0-y_1}{\sqrt{1+\left(\dfrac{y_3-y_1}{x_3-x_1}\right)^2}} \end{cases} \tag{1}$$

$$(x_i,y_i) = \frac{(x_{i-2},y_{i-2})+(x_{i-1},y_{i-1})+(x_i,y_i)+(x_{i+1},y_{i+1})+(x_{i+2},y_{i+2})}{5} \tag{2}$$

where:

$x_i(t)$ – longitudinal position of a vehicle i at time t;

$y_i(t)$ – lateral position of a vehicle i at time t;

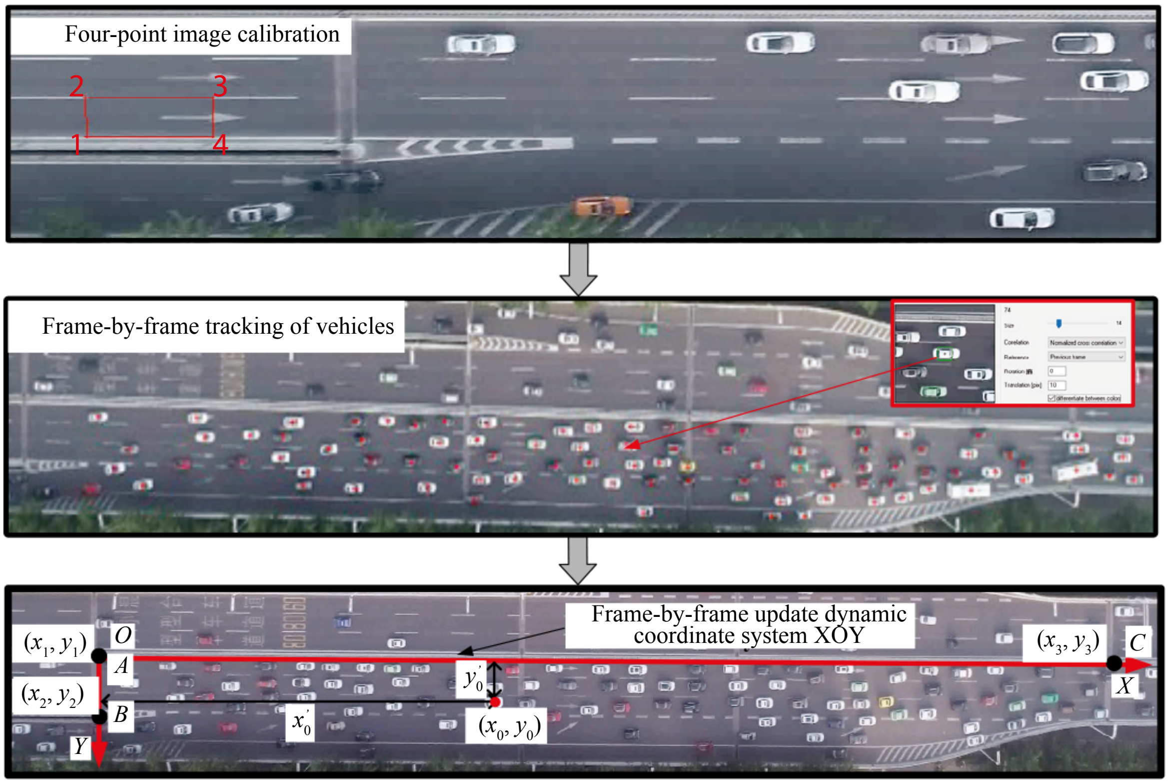

Figure 3 – Video data extraction process

3. RESULTS

3.1 Driver response characteristics

The Newell car-following model [13] captured the relationship between speed and spacing. Each driver in the queue has two independent variables (τ_i, d_i). τ_i denotes the reaction time of the rear car i, and d_i denotes the distance between the two adjacent cars when the car is blocked. Driver type characterises the driving behaviour of drivers in road traffic flow. Assuming that the wave velocity w experienced by the vehicle in the queue is constant, the Newell model shows $d=\tau w$ that only one parameter is needed to represent the driver type. In order to capture the different driver response differences, the driver type is defined from the perspective of response coefficient $\eta_i(t)$. It is the ratio of the actual car-following reaction time $\tau_i(t)$ to the reaction time τ in equilibrium [19]. In order to obtain the driver's natural response characteristics in equilibrium, the response coefficient η_i^0 in the equilibrium state before experiencing traffic oscillation is used as the driver classification index in the data measurement process. The driving styles are divided into radical, common and conservative [19], as shown in *Table 2*. Radical drivers tend to maintain a close following distance during the car-following process. The headway of conservative drivers is very large. The car-following process of common drivers is between radical and conservative. According to the classification standard of drivers' response characteristics, three types of drivers are statistically analysed based on the measured data. The results are shown in *Table 3*. This means that the share of radical type is the highest, while the share of conservative type is the smallest in the expressway merging area.

Table 2 – Classification standard of driver's type

η_i^0	$\eta_i^0<0.9$	$0.9 \le \eta_i^0 \le 1.1$	$\eta_i^0 \ge 1.1$
Driver type	Radical	Common	Conservative

Table 3 – Statistical results of driver types in the merging area

η_i^0	<0.5	0.5~0.7	0.7~0.9	0.9~1.1	1.1~1.3	1.3~1.5	>1.5
Number	5	18	82	59	51	14	6
Total	105			59	71		
Frequency	44.68%			25.11%	30.21%		

3.2 Driver response mode

After asymmetric driving behaviour was discovered and proposed, more studies verified it and constructed asymmetric behaviour models through measured data. Chen proposed an asymmetric behaviour model characterised by reaction time [11], as shown in *Figure 4*.

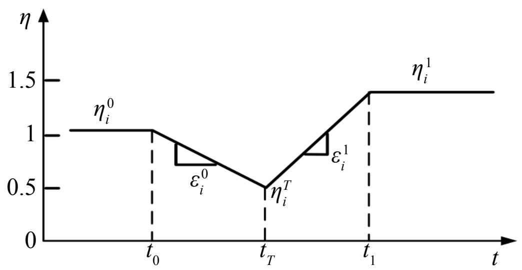

Figure 4 – Asymmetric behaviour model parameters and specific meanings

The asymmetric behaviour model contains five parameters $\{\eta_i^0, \eta_i^1, \eta_i^T, \varepsilon_i^0, \varepsilon_i^1\}$. η_i^0 represents the response coefficient under steady state before experiencing traffic oscillation. η_i^1 represents the response coefficient to steady state after traffic oscillation. η_i^T represents the maximum change in response coefficient during traffic oscillation. ε_i^0 indicates the slope of the oscillation starting reaction coefficient from the initial value to the maximum change. ε_i^1 represents the slope of the reaction coefficient from the maximum change to the new equilibrium at the end of oscillation. Different drivers have different parameter sets. In *Figure 3*, t_0, t_T and t_1 denote the time when the traffic oscillation begins, the response coefficient reaches the maximum and the oscillation ends, respectively. The relationship between the parameters can be divided into four cases according to the time sequence $\{t_0, t_T, t_1\}$. When $t \le t_0$, the driver is in stable traffic flow and the reaction coefficient remains basically unchanged, namely $\eta_i(t)=\eta_i^0$. When $t_0<t\le t_T$, the driver begins to experience traffic oscillation, and the response coefficient deviates from the initial equilibrium value. At this time $\eta_i(t)=\eta_i^0+\varepsilon_i^0(t-t_0)$. When $t_T<t\le t_1$, the driver response coefficient gradually increases to the response coefficient η_i^1 under the new equilibrium state with the end of the oscillation, and at this time $\eta_i(t)=\eta_i^T+\varepsilon_i^1(t-t_T)$. When $t \ge t_1$, the oscillation ends, the driver is in a stable traffic flow again. The reaction coefficient reaches a new equilibrium value at $\eta_i(t)=\eta_i^1$.

In the statistical distribution of asymmetric behaviour parameters, different parameter combinations correspond to different reaction modes. Data analysis found that different drivers have different response modes in non-equilibrium state, but also further illustrates the asymmetric driving behaviour in the car-following process. After classifying the response mode data of all the measured data samples, the driver response modes were preliminarily divided into four categories: non-decreasing mode, convex mode, concave mode and constant mode. However, after data analysis, it was found that convex mode and concave mode can be further subdivided into multiple sub-models according to the relationship between η^0 and η^1, as shown in *Figure 5*.

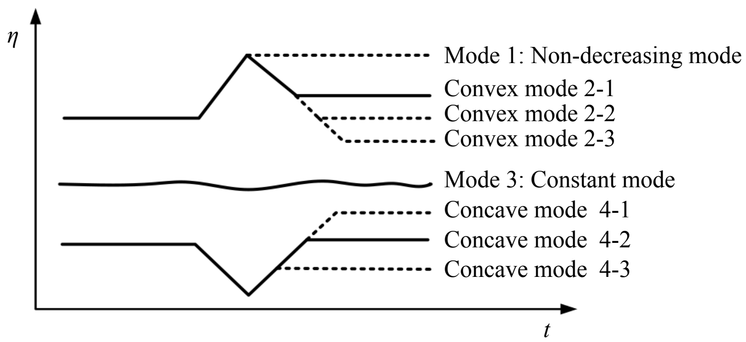

Figure 5 – Driver response mode division

Table 4 – Statistical results of the response patterns distribution of different driver types (%)

Response mode	Driver type			Total
	Radical	Common	Conservative	
Mode 1: Non-decreasing mode	14.47	5.96	5.53	25.96
Convex mode 2-1	8.09	3.40	5.53	17.02
Convex mode 2-2	4.26	2.55	1.70	8.51
Convex mode 2-3	1.28	2.55	2.13	5.96
Mode 3: Constant mode	4.26	2.98	2.55	9.79
Concave mode 4-1	5.11	3.40	7.23	15.74
Concave mode 4-2	4.66	2.14	4.26	11.06
Concave mode 4-3	2.55	2.13	1.28	5.96
Total	44.68	25.11	30.21	100.00

In order to further study the distribution patterns of different drivers, the reaction patterns of radical, common and conservative drivers were statistically analysed. The results are shown in *Table 4*. The shares of the three driver types in the constant mode are equivalent (10%). In the process of experiencing oscillation disturbance, radical drivers mainly adopt the non-reducing mode (14.47%). Common drivers mostly use the non-decreasing mode, convex mode 2-1 and concave mode 4-1, which account for about 50.82% of common drivers. Conservative drivers mainly adopt the non-decreasing mode, convex mode 2-1 and concave mode 4-1, which account for about 60.54% of conservative drivers. On the whole, the non-decreasing mode accounts for 25.96 %, the convex mode 2-1 accounts for 17.02% and the concave mode 4-1 accounts for 15.74 %. The total proportion of the three modes is 58.72%. A total of 58.72% of drivers will have a larger response coefficient after experiencing the oscillation process.

3.3 Analysis of traffic hysteresis phenomenon

Traffic hysteresis refers to the hysteresis of microscopic driver response characteristics or macroscopic speed recovery in the face of the change of front vehicle state. On the velocity-spacing plane, traffic hysteresis appears as two incompletely overlapped velocity-spacing curves. However, the appearance of traffic hysteresis affects the macro traffic flow to some extent. It is one of the main factors of traffic disturbance generation and propagation. Traffic hysteresis accelerates the formation of congestion, especially in more congested traffic conditions. The research starts with the response characteristics of individual drivers, combined with the classification of driver types, the measurement of asymmetry characteristics and the study of driver response patterns to reveal the type and distribution of traffic hysteresis. In order to deeply understand the formation process of the traffic hysteresis phenomenon, macro and micro analysis were carried out. The front vehicle speed v, the vehicle spacing s and the rear vehicle response coefficient η were extracted from the track alignment, and then the v-s and v-η curves were drawn.

Different types of drivers adopt different response modes to form different traffic delays, as shown in *Figure 6*. Traffic hysteresis mainly includes four types: clockwise hysteresis loop (a and c), counterclockwise hysteresis loop (b and d), linear hysteresis (e) and multi-loop hysteresis (f). There are different situations in the first two types of hysteresis. Taking vehicles No. 268 and No. 412 as examples, the two kinds of car-following asymmetry cause the same type of traffic delay and the time of asymmetric behaviour is different. The driver characteristics of No. 268 remained basically unchanged during the deceleration process, and began to change during the acceleration process. Driver ' s respond coefficient and the following distance of the preceding vehicle gradually increase, thus forming a positive traffic lag, namely $\Delta\eta>0$, $\Delta s>0$. The respond characteristics of the car No. 412 deviate from the initial state in the process of deceleration but remain basically unchanged in the process of acceleration. Therefore, a negative traffic lag is formed, namely $\Delta\eta<0$, $\Delta s<0$. Similarly, the reaction process of cars Nos. 315 and 622 can also be divided into two cases.

According to the driver type, the driver's reaction mode and the change of reaction coefficient during acceleration and deceleration, the traffic delay results of all samples are summarised as shown in *Table 5*. Positive traffic hysteresis means that larger vehicle spacing or headway lead to delays. On the contrary, reverse traffic hysteresis can increase the passing rate of the merging area to some extent. Drivers in the non-decreasing mode and convex mode mainly produce positive clockwise traffic hysteresis during acceleration, and positive counterclockwise traffic hysteresis during deceleration. Drivers in the concave mode mainly produce negative counterclockwise traffic hysteresis during acceleration, and negative clockwise traffic hysteresis during deceleration.

In order to quantitatively analyse the traffic hysteresis caused by asymmetric driving behaviour in car-following, the statistics of various hysteresis types and corresponding change index values are shown in *Table 6*. Two results can be seen from *Table 6*. Firstly, the hysteresis types are mainly clockwise and counterclockwise, accounting for 79.38 %. The proportions of various hysteresis types from large to small are $CCW^{+}>CW^{+}>M>CW^{-}>CCW^{-}>L$. Secondly, it can be seen that the cumulative change of the reaction

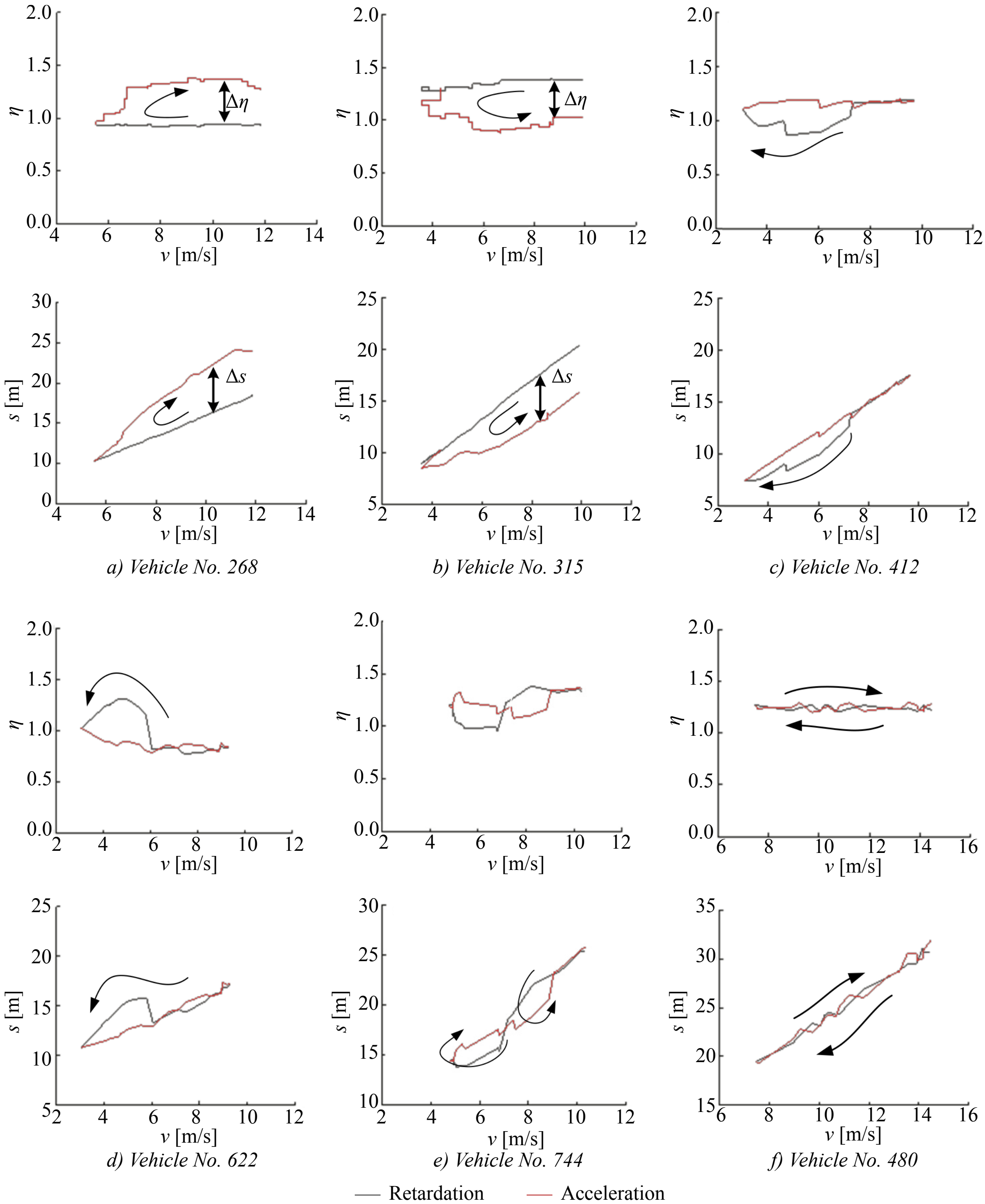

Figure 6 – Case analysis of different traffic hysteresis types

Table 5 – Analysis results of traffic hysteresis types

Types of traffic hysteresis	Driver's car-following reaction mode							
	Mode 1: Non-decreasing mode	Convex mode 2-1	Convex mode 2-2	Convex mode 2-3	Mode 3: Constant mode	Concave mode 4-1	Concave mode 4-2	Concave mode 4-3
Stage 1	CW^+	CW^+	CW^+	M	L	M	CCW^-	CCW^-
Stage 2	CCW^+	CCW^+	CCW^+	CCW^-	L	CCW^+	CW^-	CW^-

Note: Stage 1 – change of reaction coefficient in acceleration process, Stage 2 – change of response coefficient in deceleration process, – clockwise hysteresis loop, – counter clockwise hysteresis loop, – linear hysteresis, – multi-loop hysteresis, ‘ + ‘ – positive hysteresis, ‘ – ‘ – negative hysteresis.

coefficient of all the samples is greater than 0, about 0.15. It shows that the traffic delay caused by asymmetric driving behaviour in the merging area is generally positive, and the average driver reaction time is larger than that of the equilibrium state, which leads to an increase in traffic delay.

Table 6 – Statistical results of traffic hysteresis distribution

Types of traffic hysteresis	Average change of reaction coefficient $\overline{\Delta\eta}$	Frequency p (%)	Variable quantity
CW^+	0.384	27.75	0.10656
CCW^+	0.289	31.61	0.091353
CW^-	-0.342	10.14	-0.034679
CCW^-	-0.253	9.88	-0.024996
L	0.046	9.79	0.004503
M	0.079	10.83	0.008556
Total	-	100	0.151297

3.4 Capacity analysis

In Newell's theory, if the driver's characteristics do not change, the car-following vehicle will maintain the same trajectory as the front vehicle, and the existence of asymmetric behaviour will cause the car-following vehicle trajectory to deviate from the front vehicle trajectory. The study combines Newell model [5], AB model [11] and motion wave theory to explore the influence of asymmetric behaviour on the bottleneck outflow rate in the merging area. Finally, the bottleneck outflow rate of merging area is quantitatively analysed.

The bottleneck outflow rate in the merging area is calculated by the reciprocal of the average headway. The basic model is shown in *Formula 3*. As shown in *Formula 4*, q represents the bottleneck outflow rate in the merging area. $\bar{h}$ represents the average headway of the main stream in the merging area. Δt_i represents the time interval between the rear vehicle and the car i. n represents the number of all vehicles. For vehicle i, the time interval includes two parts. One is the reaction time τ_i. The second is the movement time t_r, which is expressed as the movement time of vehicle i to the front of the vehicle. $\bar{v}$ represents the average speed of vehicles in the merging area. The details are shown in *Formula 4*. Through the *Formulas 3 and 4*, the bottleneck outflow rate in the merging area can be further solved as shown in *Formula 5*.

$$q=\frac{1}{\bar{h}}=\frac{n}{\sum_{i=1}^{n}\Delta t_i} \tag{3}$$

$$t_r=\frac{\tau_i w}{\bar{v}} \tag{4}$$

$$q=\frac{n}{\sum_{i=1}^{n}\left(\tau_i+\frac{\tau_i w}{\bar{v}}\right)} \tag{5}$$

According to $\tau_i=\eta_i\tau$, the final solution model can be obtained as shown in *Formula 6*. Newell's model is used to calculate the bottleneck outflow rate as shown in *Formula 7*. The bottleneck outflow rate q_1 is calculated by the asymmetric behaviour model as shown in *Formula 8*.

$$q=\frac{n}{\sum_{i=1}^{n}\eta_i\tau\left(\frac{w+\bar{v}}{\bar{v}}\right)} \tag{6}$$

$$q_0 = \frac{n}{\sum_{i=1}^{n} \eta_i^0 \tau\left(\frac{w+\bar{v}}{\bar{v}}\right)} \tag{7}$$

$$q_1 = \frac{n}{\sum_{i=1}^{n} \eta_i^1 \tau\left(\frac{w+\bar{v}}{\bar{v}}\right)} \tag{8}$$

In order to describe the influence of asymmetric driving behaviour on the bottleneck outflow rate more clearly, the relative reduction c_{AB} was calculated. The calculation model is shown in *Formula 9*. In *Formula 10*, the specific value can be obtained by knowing the mean value of the driver's initial response coefficient and the disturbance end response coefficient. In order to fully consider the influence of different driver response characteristics on c_{AB}, the driver's response mode j and its probability p_j are average weighted as shown in *Formula 10* when calculating the mean value of response coefficient.

$$c_{AB} = \frac{q_0 - q_1}{q_0} = 1 - \frac{\sum_{i=1}^{n} \eta_j^0}{\sum_{i=1}^{n} \eta_j^1} = 1 - \frac{\overline{\eta_j^0}}{\overline{\eta_j^1}} \tag{9}$$

$$c_{AB} = 1 - \frac{\sum p_j \overline{\eta_j^0}}{\sum p_j \overline{\eta_j^1}} \tag{10}$$

c_{AB} is calculated from *Formula 10* and the statistical results of the distribution of different reaction modes in *Table 4*. The calculation results of the eight reaction modes are shown in *Table 7*. Due to drivers' asymmetric behaviour in the expressway merging area, the outflow rate is reduced by about 7 % on average. This also shows that the decline of traffic capacity in the merging area is related to drivers' asymmetric behaviour.

Table 7 – Influencing coefficient calculation results of asymmetric behaviour in merging area

j	Mode 1: Non-decreasing mode	Convex mode 2-1	Convex mode 2-2	Convex mode 2-3	Mode 3: Constant mode	Concave mode 4-1	Concave mode 4-2	Concave mode 4-3
$p_j \overline{\eta_j^0}$	0.2232	0.1549	0.0749	0.0548	0.1037	0.1858	0.1383	0.0822
$p_j \overline{\eta_j^1}$	0.3167	0.1583	0.0732	0.0423	0.1057	0.1937	0.1372	0.0679
C_{AB}	0.0705							

4. DISCUSSION

Continuous vehicle trajectories under various traffic flow states were obtained by aerial photography in Hefei, China. The basic parameters of traffic flow and vehicle operation characteristics are extracted by using SIMI motion, manual counting and MATLAB. On this basis, the driver response mode under the asymmetric driving behaviour characteristics in the expressway merging area is analysed. The asymmetric behaviour characteristics under the influence of traffic hysteresis and the impact on capacity are further revealed.

Driver response mode in asymmetric behaviour

The relationship between the driver's initial response coefficient and the rebalance response coefficient is used to characterise asymmetric behaviour. At the same time, driver response mode is further divided by the response coefficient before and after the traffic oscillation. Many studies have classified driver types [22–24]. However, the driver 's response mode is mainly divided into four modes, which is not divided in more detail. For example, Babak Mirbaha uses NGSIM data to divide into four behaviour patterns based on driver performance differences. These are two modes of underreaction and overreaction in the decelerating phase, and two modes of behaviour divided into radical and conservative types based on hysteresis in the accelerating phase [25].

In the process of experiencing oscillation disturbance, radical, conservative and common drivers mainly adopt the non-reducing mode, concave mode 4-1 and convex mode 2-1, respectively. In general, 58.72% of drivers will have a larger response coefficient after experiencing the oscillation process. However, an analysis of NGSIM data by Chen et al. shows that the share of common drivers is higher in 111 pairs of trajectories (about 58%). Radical drivers still have enough risk-taking spirit after traffic oscillation, which takes convex mode to further reduce the interval and maintain radical characteristics. Conservative drivers clearly prefer convex mode over concave mode. Common drivers tend to remain in constant mode [10]. This is different from the reaction mode adopted by the driver in the process of oscillation. Before the driver encounters the oscillation, the share of common drivers is the lowest (25.11%) in 235 pairs of trajectories, and the polarisation of driving characteristics is more significant. This may be due to the significant differences between Chinese and American drivers [19].

Traffic hysteresis

The proportion of various types of traffic hysteresis $CCW^{+}>CW^{+}>M>CW^{-}>CCW^{-}>L$. Different driver response modes will produce different types of traffic hysteresis. The traffic hysteresis caused by asymmetric driving behaviour in the merging area is generally positive, and the average driver reaction time is larger than that in the equilibrium state. Traffic hysteresis between drivers are inconsistent. Safety distance between vehicles is affected by driving characteristics [1, 26]. Drivers' characteristics are an important factor affecting the magnitude of traffic hysteresis [27–28]. In the process of deceleration radical drivers are more reluctant to slow down than conservative drivers. On the other hand, conservative drivers are more inclined to slow down. During acceleration, radical drivers rush to accelerate to catch up with the front vehicle. Conservative drivers are slower when it comes to speeding ahead of the chase. Positive traffic hysteresis means that larger vehicle spacing or headway will bring certain delays. On the contrary, reverse traffic hysteresis can increase the passing rate of the merging area to some extent. Some scholars have found that most of the hysteresis loops (66%) in traffic hysteresis are positive and about 14 % are negative [29]. Therefore, traffic hysteresis can be suppressed by balancing driver characteristics.

Traffic capacity

Asymmetric driving behaviour in expressway merging areas causes the bottleneck outflow rate of the merging area to decrease by 7 % on average, resulting in a decrease in traffic capacity. Traffic delays are caused by the variable driving characteristics of each driver. They also have a profound impact on the periodicity and development of traffic oscillations and bottleneck emission rates. The traffic delay caused by driver's asymmetric behaviour in merging areas is generally positive. The average driver reaction time is larger than that in equilibrium. This is basically consistent with studies showing that the bottleneck emission rate can be reduced by 8–23 % when the driver takes a greater response time to the shock [20, 30]. This also shows that the view that the capacity decline in the merging area is mainly caused by lane change is incomplete.

Nevertheless, there are still some limitations in this paper. This study focuses on the car-following effect without considering the influence of lane change. Further research is needed to better understand the interaction of these behaviours in the development of oscillations and bottleneck emission rates. The data used in this study is only from Hefei, China. The data is relatively limited. More extensive data collection is needed in future research. It should include not only vehicle trajectory data, but also video clips that capture driver's head/eye movement.

5. CONCLUSION

The aerial photography technology was used to collect traffic flow data in Hefei city. The characteristics of asymmetric driving behaviour were revealed by means of $\{\eta_i^0, \eta_i^1, \eta_i^T, \varepsilon_i^0, \varepsilon_i^1\}$ when each driver experiences traffic oscillation. The influence of asymmetric driving behaviour is studied quantitatively. The results are as follows:

The share of driver types in expressway merging areas is the highest for the radical type and the lowest for the common type. According to the relationship between η^0 and η^1, the driver response modes are divided into four categories: non-decreasing mode, convex mode, concave mode and constant mode. On this basis, the convex mode and concave mode are subdivided into multiple sub-models. Radical, conservative and common drivers mainly adopt the non-decreasing mode, concave mode 4-1 and convex mode 2-1 in the process of experiencing oscillation disturbance. The reaction coefficient of radical drivers generally increases during oscillation. Only a few common drivers become radical after oscillations. Most of the conservative drivers keep cautious driving after oscillation.

The main types of traffic hysteresis are clockwise and counterclockwise, accounting for about 79.38 %. The proportion of various types of traffic hysteresis is $CCW^+>CW^+>M>CW^->CCW^->L$. The traffic hysteresis caused by drivers' asymmetric following behaviour in the merging area is generally positive. Driver 's average reaction time after traffic oscillation is higher than in equilibrium, resulting in increased traffic delay. At the same time, asymmetric driving behaviour causes the bottleneck outflow rate of the merging area to decrease by about 7%, which leads to traffic capacity decrease.

The study further divides the driver response modes and explores the impact of asymmetric behaviour on traffic delay. In the future, more research can be done on how to predict the response patterns of different types of drivers to traffic oscillations. In other words, it is to suppress the impact of traffic delays by balancing driver characteristics. This is of great significance for formulating efficient congestion mitigation strategies and analysing the mechanism of congestion propagation.

ACKNOWLEDGEMENT

This study was supported by the National Natural Science Foundation (51878236). The author would like to thank the state funding and all the participants for their assistance.

REFERENCES

[1] Sun P, Wang X, Zhu M. Modeling Car-Following Behavior on Freeways Considering Driving Style. *Journal of Transportation Engineering, Part A: Systems.* 2021;147(12). DOI: 10.1061/JTEPBS.0000584.

[2] Suh J, Yeo H. An empirical study on the traffic state evolution and stop-and-go traffic development on freeways. *Transportmetrica A: Transport Science.* 2016;12(1):80-97. DOI: 10.1080/23249935.2015.1101508.

[3] Kordani AA, Saffarzadeh M, Salehikalam A. Identifying and analyzing stop and go traffic based on asymmetric theory of driving behavior in acceleration and deceleration. *International Journal of Transportation Engineering.* 2016;3(4):237-252. DOI: 10.22119/IJTE.2016.16170.

[4] Park M, Kim Y, Yeo H. Development of an Asymmetric car-following model and simulation validation. *IEEE Transactions on Intelligent Transportation Systems.* 2020;21(8):3513-3524. DOI: 10.1109/tits.2019.2930320.

[5] Newell GF. *Instability in dense highway traffic: A review*. 1965; p. 9-54.

[6] Hao Xu, et al. Modeling the asymmetry in traffic flow (a): Microscopic approach. *Applied Mathematical Modelling.* 2013;37(22). DOI: 10.1016/j.apm.2013.04.037.

[7] Wang K, et al. Research on Car-Following Model considering Driving Style. *Mathematical Problems in Engineering.* 2022;2022. DOI: 10.1155/2022/7215697.

[8] Suh J, Yeo H. A study on the wave development and evolution characteristics of stop-and-go traffic. *Proceedings of the Eastern Asia Society for Transportation Studies*. 2011.

[9] Li X-C. *Modeling and analysis of car-following behavior considering the asymmetry* [考虑非对称特性的车辆跟驰行为建模与分析]. Master Degree Thesis. Southwest Jiaotong University; 2019.

[10] Qian, et al. Using asymmetric theory to identify heterogeneous drivers' behavior characteristics through traffic oscillation. *IEEE Access*. 2019;7:106284-106294. DOI: 10.1109/ACCESS.2019.2930762.

[11] Chen D, et al. Microscopic traffic hysteresis in traffic oscillations: A behavioral perspective. *Transportation Research Part B: Methodological.* 2012;46(10):1440-1453. DOI: 10.1016/j.trb.2012.07.002.

[12] Wei D, Liu H. Analysis of asymmetric driving behavior using a self-learning approach. *Transportation Research Part B: Methodological.* 2013;47:1-14. DOI: 10.1016/j.trb.2012.09.003.

[13] Newell GF. Theories of instability in dense highway traffic. *Journal of the Operations Research Society of Japan.* 1962;1(5):9-54.

[14] Yeo H, Skabardonis A. Understanding stop-and-go traffic in view of asymmetric traffic theory. *Transportation & Traffic Theory.* 1970.

[15] Wong GCK, Wong SC. A multi-class traffic flow model – an extension of LWR model with heterogeneous drivers. *Transportation Research Part A: Policy and Practice.* 2002;36(9):827-841. DOI: 10.1016/s0965-8564(01)00042-8.

[16] Ahn S, et al. A method to account for non-steady state conditions in measuring traffic hysteresis. *Transportation Research Part C: Emerging Technologies*. 2013;34:138-147. DOI: 10.1016/j.trc.2011.05.020.

[17] Laval JA. Hysteresis in traffic flow revisited: An improved measurement method. *Transportation Research Part B: Methodological.* 2011;45(2):385-391. DOI: 10.1016/j.trb.2010.07.006.

[18] Li X, et al. An improved car-following model considering the influence of space gap to the response. *Physical A: Statistical Mechanics and Its Applications.* 2018;509:536-545. DOI: 10.1016/j.physa.2018.06.069.

[19] Chen D, et al. A behavioral car-following model that captures traffic oscillations. *Transportation Research Part B: Methodological.* 2012;46(6):744-761. DOI: 10.1016/j.trb.2012.01.009.

[20] Chen D, et al. On the periodicity of traffic oscillations and capacity drop: the role of driver characteristics. *Transportation Research Part B: Methodological.* 2014;59:117-136. DOI: 10.1016/j.trb.2013.11.005.

[21] Yang X, et al. Biomechanics analysis of human walking with load carriage. *Technology and Health Care.* 2015;23(s2). DOI: 10.3233/THC-150995.

[22] Lajunen T, Summala H. Can we trust self-reports of driving? Effects of impression management on driver behaviour questionnaire responses. *Transportation Research Part F: Psychology and Behaviour.* 2003;6(2):97-107. DOI: 10.1016/S1369-8478(03)00008-1.

[23] Pesti G, et al. Simulation of weaving traffic between freeway ramps. *Transportation Research Board 90th Annual Meeting, 23-27 Jan. 2011, Washington DC, United States*. 2011.

[24] Rong J, Mao K, Ma J. Effects of individual differences on driving behavior and traffic flow characteristics. *Transportation Research Record*. 2011;2248:1-9. DOI: 10.3141/2248-01.

[25] Mirbaha B, Kordani AA, Salehikalam A, Zarei M. Analyzing stop time phase leading to congestion based on drivers' behavior patterns. *Tarrahan Parseh Transportation Research Institute.* 2018;(4). DOI: 10.22119/IJTE.2018.49734.

[26] Wang J, Chai R, Xue X. The effects of stop-and-go wave on the immediate follower and change in driver characteristics. *Procedia Engineering*. 2016;137:289-298. DOI: 10.1016/j.proeng.2016.01.261.

[27] Saifuzzaman M, Zheng Z, Haque MM, Washington S. Understanding the mechanism of traffic hysteresis and traffic oscillations through the change in task difficulty level. *Transportation Research Part B: Methodological.* 2017;105:523-538. DOI: 10.1016/j.trb.2017.09.023.

[28] Deng H, Zhang HM. On traffic relaxation, anticipation, and hysteresis. *Transportation Research Record*. 2015;2491(1):90-97. DOI: 10.3141/2491-10.

[29] Laval JA. Hysteresis in traffic flow revisited: An improved measurement method. *Transportation Research Part B: Methodological.* 2010;45(2):385-391. DOI: 10.1016/j.trb.2010.07.006.

[30] Chen D, Ahn S. Capacity-drop at extended bottlenecks: Merge, diverge, and weave. *Transportation Research Part B: Methodological.* 2018;108(2):1-20. DOI: 10.1016/j.trb.2017.12.006.

张卫华，韦丝平，王昌胜，邱猛

快速路合流区不对称行为特征及交通流特性

摘要

车辆在跟驰下表现出不同的特征，这种差异反映了驾驶风格，是交通不确定性的重要组成部分。研究深入挖掘不对称驾驶行为下的驾驶特性及其对交通流特性的影响，以提高对驾驶和其他一些安全性研究的理解。通过无人机航拍获取快速路合流区的多种交通流状态下连续车辆运行轨迹， 提取出交通流基本参数及车辆运行特征数据。基于实测数据将驾驶员反应模式细分为多种子模式，在此基础上进一步揭示交通迟滞的类型和分布以及不对称行为对合流区通行能力的影响。结果表明在经历振荡扰动到重新达到平衡的过程中，总体上驾驶员反应系数会变大，激进型主要采用反应系数达到最大值的非减模、保守型主要采用凹形模式中平衡时的反应系数大于初始反应系数的反应模式、普通型驾驶主要采用凸形模式中平衡时的反应系数介于初始反应系数与反应系数峰值的反应模式，快速路合流区驾驶员跟车不对称行为产生的交通迟滞总体上是正向的，且不对称行为致使合流区瓶颈流出率平均降低约7%，导致延误增加与通行能力下降。本研究对于分析交通拥堵形成机理，制定有效的防控措施具有重要的实际意义。

关键词：

快速路；合流区；不对称行为；驾驶员反应模式；交通迟滞；通行能力