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Analysis of Chinese Typical Lane Change Behavior in Car–Truck Heterogeneous Traffic Flow from UAV View

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Abstract: Chinese driver behavior in heterogeneous traffic is commonly available, but it is difficult to acquire due to view limitations and sensor limitations. In this study, Chinese typical lane change behavior in car-truck heterogeneous traffic flow was collected and analyzed using an Unmanned Aerial Vehicle (UAV). The velocity of ego vehicle, relative velocity and distance of ego and surrounding vehicles, time to collision (TTC), time headway (THW) at the lane change moment, and brake and accelerate reaction time during lane changes were investigated. Results showed that large differences existed in various car follow types and lane change types. Cars drove more aggressively than trucks with shorter reaction times, and cars would change lanes at a longer distance when facing trucks. Smaller TTC and THW were found for trucks when facing cars. Chinese drivers showed more frequent lane-change maneuvers and shorter reaction times compared to other countries. The driver characteristic in China provided data support for the training of artificial intelligence-based decision algorithms, the development of a localized system, and the design of roads.

Keywords: Chinese driving behavior; big data; lane change; heterogeneous traffic; UAV view

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1. Introduction

Car–Truck heterogeneous traffic flow has commonly existed on highways. Knowing the cars and trucks' lane change behavior in heterogeneous traffic and their differences were helpful for the localization of intelligent connected vehicles, both in the aspect of enhancing the safety of autonomous driving (AD) and advanced driving assistance system (ADAS) and the aspect of improving the traffic efficiency. To better describe the driving behavior, many researchers have conducted investigations based on naturalistic driving data. The second Strategic Highway Research Program (SHRP2) in the United States and the China Automotive Engineering Research Institute Company and Tongji University in China have collected data from more than one million kilometers [1–4]. ADAS systems such as adaptive cruise control (ACC) [5], an automatic emergency brake system (AEB) [6], lane-keeping assistance system (LKA) [7], and automatic parking system (APS) [8] were developed using these data. They were also used in human behavior recognition, traffic light detection, and corner cases mining based on deep learning methods [9–11]. Typical behavior, such as free driving, car following, lane changing, and overtaking, were analyzed, and control models were built [12–14].

Driving behavior, especially in heterogeneous traffic, was not only affected by the front vehicles but the surrounding vehicles or even the vehicles outside the surrounding one. However, the influence of indirect factors, such as the vehicle in front of the front

vehicle, can not be described by naturalistic driving data using vehicular-based equipment because of the visual block. Road-side cameras were used in collecting and analyzing driving behavior [15]. Fan et al. collected data on a typical highway in the US and analyzed the time headway distribution of different vehicle combinations [16]. Li et al. built a two-lane cellular automata model to investigate the influence of the car and truck portion on traffic characteristics [17]. Bird view cameras were either used in the collection or analysis of the driving behavior. Next-generation simulation (NGSIM) dataset collected 90 min video of the I80, US101, lane and peach highway in the US using cameras equipped in tall buildings [18]. The Highway Drone (HighD) dataset collected more than 17 h of video on major German highways using an Unmanned Aerial Vehicle (UAV) with higher precision [19]. By using these data, microscopic driving behavior and macroscopic traffic characteristics were deeply investigated [20–23]. Friedrich Krube et al. made a macroscopic and microscopic analysis for HighD [24], and Valentina Kurtc calibrated a two-car-following model based on it [25]. Yang et al. established a car-following model considering the combination of car and truck in the same lane [26]. Kong et al. introduced the lane change maneuver into the cellular automata model and improved the model fidelity [27,28].

Most investigations used data from US and Europe, which cannot represent the characteristics in China, considering the difference between drivers. In order to improve the adaptability of AD and ADAS system in a domestic situation, related research was conducted in China. Kong et al. analyzed the vehicle headway distribution on multi-lane free-ways when considering car–truck interactions through the cameras set on the highway [29]. Gao et al., Liang et al., and Zhang et al. analyzed the effect on the velocity, stability, and safety parameters after trucks were introduced into the traffic [30–32]. However, the characteristics were not fully captured due to visual limitations. Jiang et al. performed a platoon driving test containing 25 vehicles and analyzed the characteristics during long-distance driving [33]. However, it cannot represent the whole characteristics as the lane change maneuver was restricted.

This study aimed to overcome the visual limitation using vehicle-based data acquisition equipment and compare the driver behavior difference between various countries. We focused on the typical lane change behavior on Chinese highways collected by drones which can fully capture the characteristics of heterogeneous traffic. Analysis of the behavioral difference, including velocity, distance, time to collision (TTC), and time headway (THW) between various car follow types and lane change types, were performed. The reaction time when cut in and cut out was also investigated. The driver characteristics in heterogeneous traffic in China were investigated in this study, which provides data support for the understanding of behavioral differences between countries and the development of localized AD and ADAS systems.

2. Materials and Methods

Six highway sections in Guangzhou and Shanghai were selected for data collection, with three straight driving lanes in each direction. About 17 h videos were acquired, and the average length is 15 min. DJI Phantom 4 Pro V2.0 (SZ DJI Technology Co., Ltd., Shenzhen, China) was used, and 4K resolution video with 30 fps was captured. One drone was flying directly above the highway section between 8 a.m. and 6 p.m. while the weather was clear and the road surface was dry.

The detailed procedure was discussed in a former study, so it was briefly introduced in this one [34]. Automatic relative rotation correction combining Speed Up Robust Features (SURF) and Fast Library for Approximate Nearest Neighbors (FLANN) algorithms and manual absolute rotation correction were firstly performed to eliminate the video rotation due to wind in the sky. Transfer learning for Deep Neural Network (DNN) model was then used as the detection tool [35]. Tracking algorithm based on optical flow was used to track each vehicle [36]. Locally weighted regression (LOESS) method was used to smooth the displacement, velocity, and acceleration. Other parameters, such as TTC and

THW, can be calculated based on the trajectory information. Trajectory generation workflow and the detection result are shown in Figure 1. The displacement error is 10 cm as a pixel in the image was about $10\text{ cm} \times 10\text{ cm}$.

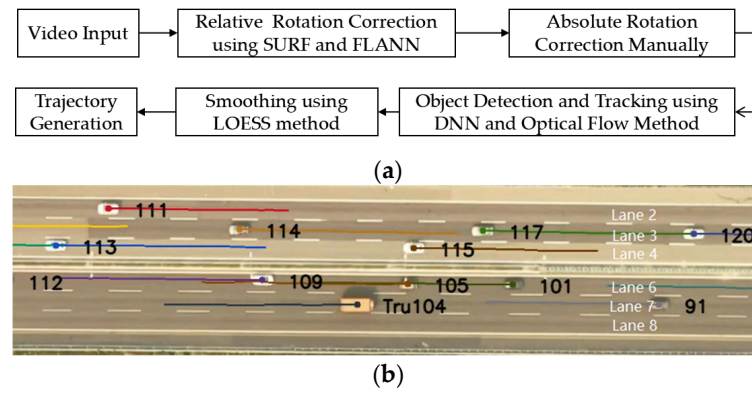


Figure 1. (a) Trajectory generation workflow [34] and (b) the detection result.

The lane change participant and moment definition are shown in Figure 2. The ego vehicle was defined as m . The front vehicle in the same lane was $n1$, and the one in the next lane was $n2$. The following vehicle in the same lane was $n4$, and the one after $n4$ was $n6$. The following vehicle in the next lane was $n3$, and the one after $n3$ was $n5$. Slow, middle, and fast lane in upper road were defined as lanes 2, 3, and 4, and they were defined as lanes 8, 7, and 6 in lower road, as shown in Figure 1b. Combining the lane change direction and the lane when the behavior happened, the lane change types were classified as right lane change in fast lane (Fast-Right), right lane change in middle lane (Middle-Right), left lane change in middle lane (Middle-Left) and left lane change in slow lane (Slow-Left) and they were labeled as 1, 2, 3, and 4. The car follow types, namely, heterogeneous combinations, were classified as car-car (C-C), car-truck (C-T), truck-car (T-C) and truck-truck (T-T). Three vehicle platoon was defined as three vehicles in which THW is less than 5 s between the lead and the follow vehicles. They were classified as car-car-car (C-C-C), car-truck-car (C-T-C), truck-car-car (T-C-C), truck-truck-car (T-T-C), car-car-truck (C-C-T), car-truck-truck (C-T-T), truck-car-truck (T-C-T) and truck-truck-truck (T-T-T) [4]. Lane change moment was defined as the starting point with the largest lateral displacement before the vehicle crossed the lane.

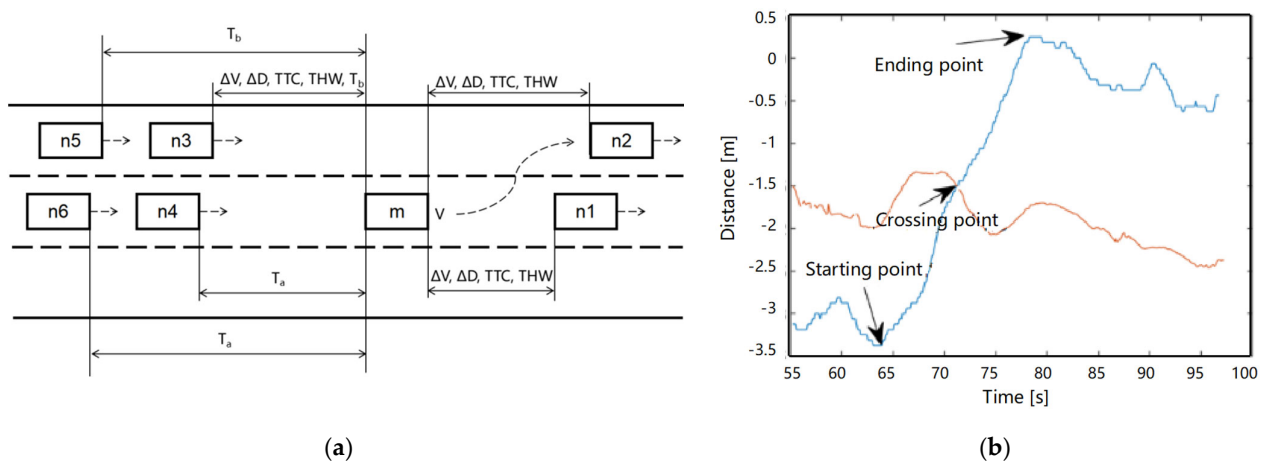


Figure 2. Lane change (a) participant definition and (b) moment definition.

The velocity of m , relative velocity (ΔV), and distance (ΔD) of m and surrounding vehicles, TTC and THW, at the lane change moment were investigated. The brake reaction time (T_b) of $n3$ and $n5$ and the acceleration reaction time (T_a) of $n4$ and $n6$ were also studied. The mentioned parameters were subjected to the Kolmogorov–Smirnov test to evaluate the presence of a normal distribution. If normally distributed, they were subjected to a one-way analysis of variance for lane change types and vehicle following types. If not, a non-parametric Kruskal–Wallis test was performed. Post hoc pairwise comparisons using Tukey’s honestly significant difference method were performed if there were significant differences. An alpha level of 0.05 was used. The mean and standard deviation (SD) were calculated for all parameters. Only TTC with less than 100 was studied.

3. Results

3.1. Lane Change Statistic

More than 910,000 vehicles were captured, consisting of 800,000 cars and 110,000 trucks. The driving distance was about 37,000 km, and the driving duration was 443 h. A total of 22,012 cases of lane change were acquired and 1120 of them were free lane changes with no vehicle ahead, so they were not investigated in this study. Car-related lane changes commonly existed due to a large number of cars. Despite the regulation required that trucks should drive in the middle and slow lane, dozens of trucks were driving in the fast lane when lane change started or left changed from middle to fast lane. When considering the mass and volume of trucks, the potential driving risk was raised, although the velocity was low. The regulation also resulted in a mixture of cars and trucks in the middle and slow lanes, namely high traffic heterogeneity. The statistic of lane change frequency of different car follow types and lane change types was shown in Table 1.

Table 1. Lane change frequency.

Combination	Fast-Right	Middle-Right	Middle-Left	Slow-Left
C-C	5236	3965	4188	3104
C-T	12	768	1122	1090
T-C	17	406	19	366
T-T	-	273	9	317

3.2. Macroscopic Results

The relationship between total lane change times and flow rate and density is shown in Figure 3. Lane change in the middle lane is distributed in all flowrate and density regions, while in the fast lane, it is concentrated on where the flowrate is in [750, 1500] and density is in [8, 13], and in the slow lane, it is concentrated on where flowrate is in [300, 750] and density is in [5, 8]. The relationship between total lane change times and the truck portion is shown in Figure 4. With the increase in truck portion, lane change times in the middle and slow lane decreased, and that in the middle lane showed a larger amount.

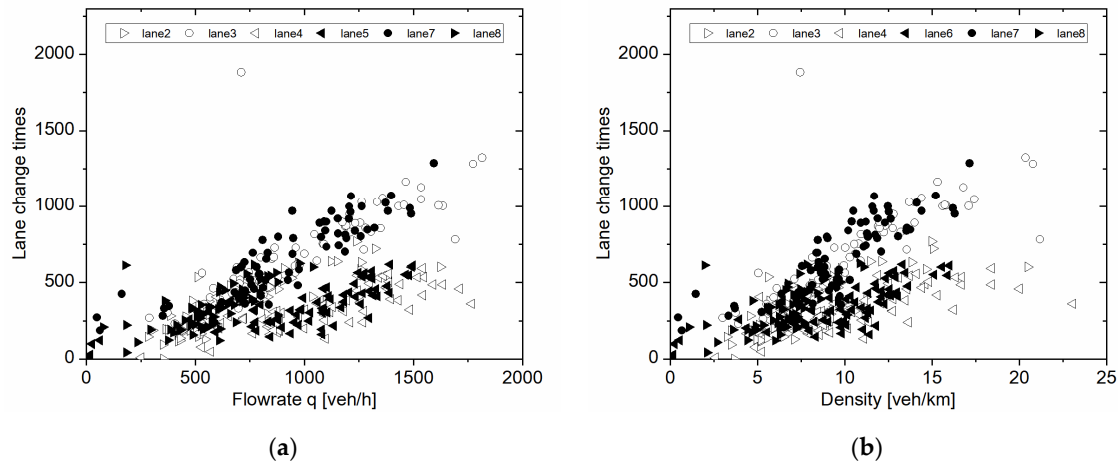


Figure 3. (a) Total lane change times versus flow rate; (b) Total lane change times versus density.

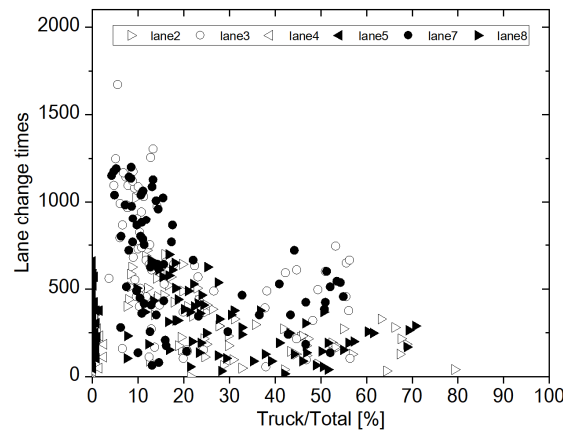


Figure 4. Total lane change times versus truck portion.

3.3. Microscopic Results

The probability distribution of m velocity and the differences in the car follow types and lane change types are shown in Figure 5. The velocity of m is distributed in $[90, 100]$, which is higher than the mean one, especially for the car-car pair [37]. Some of them even exceeded the highest speed limit of 120 km/h, indicating that part of aggressive drivers showed illegal behavior when changing lanes. Significant differences were found between various car follow types and lane change types. Probability distribution of ΔV and ΔD between m and $n1$, $n2$ and $n3$, and the differences of car follow types and lane change types were shown in Figures 6 and 7. ΔV_{m-n1} and ΔV_{m-n3} were larger than 0 at lane change moments, and ΔV_{m-n2} were smaller than ΔV_{m-n1} , meaning that a better driving situation exists after the lane change, especially for cars. ΔD_{m-n1} and ΔD_{m-n2} are distributed in $[20, 50]$. Significant differences were found for all ΔV and ΔD between various car follow types and lane change types. Probability distribution of TTC and THW between m and $n1$, $n2$ and $n3$, and the differences of car follow types and lane change types, are shown in Figures 8 and 9. TTC_{m-n1} is distributed in $[0, 20]$ and THW_{m-n1} in $[0, 2]$ at the lane change moment while TTC_{m-n2} in $[10, 30]$ and THW_{m-n2} in $[1, 3]$. TTC_{m-n3} and THW_{m-n3} were smaller. The mean and standard deviation of T_b of $n3$ and $n5$ and their differences are shown in Tables 2–4. The mean and standard deviation of T_a of $n4$ and $n6$ and their differences are shown in Tables 5–7. T_b is distributed in $[0.9, 1.67]$ and T_a was higher. No significant differences were found for T_b and T_a between various car follow types and lane change types. The

mean and standard deviation of other parameters were shown in Appendix A and significant difference of parameters were shown either, where Table A1 represented the m velocity, Table A2-A4 represented the ΔV of m and $n1$, $n2$, $n3$, Table A5-A7 represented the ΔD of m and $n1$, $n2$, $n3$, Table A8-A10 represented the TTC of m and $n1$, $n2$, $n3$, and Table A11-A13 represented the THW of m and $n1$, $n2$, $n3$,

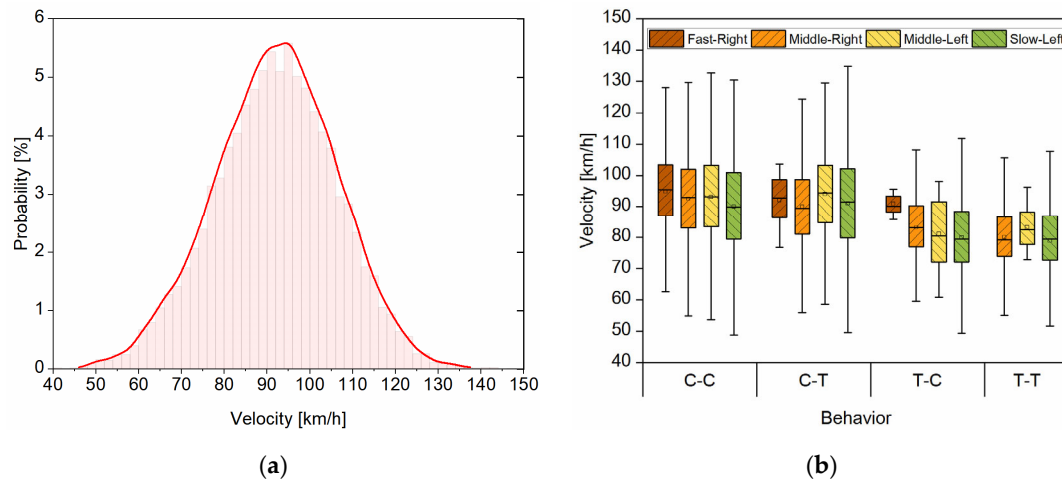


Figure 5. (a) Probability distribution of m velocity; (b) Velocity in different car follow types and lane change types.

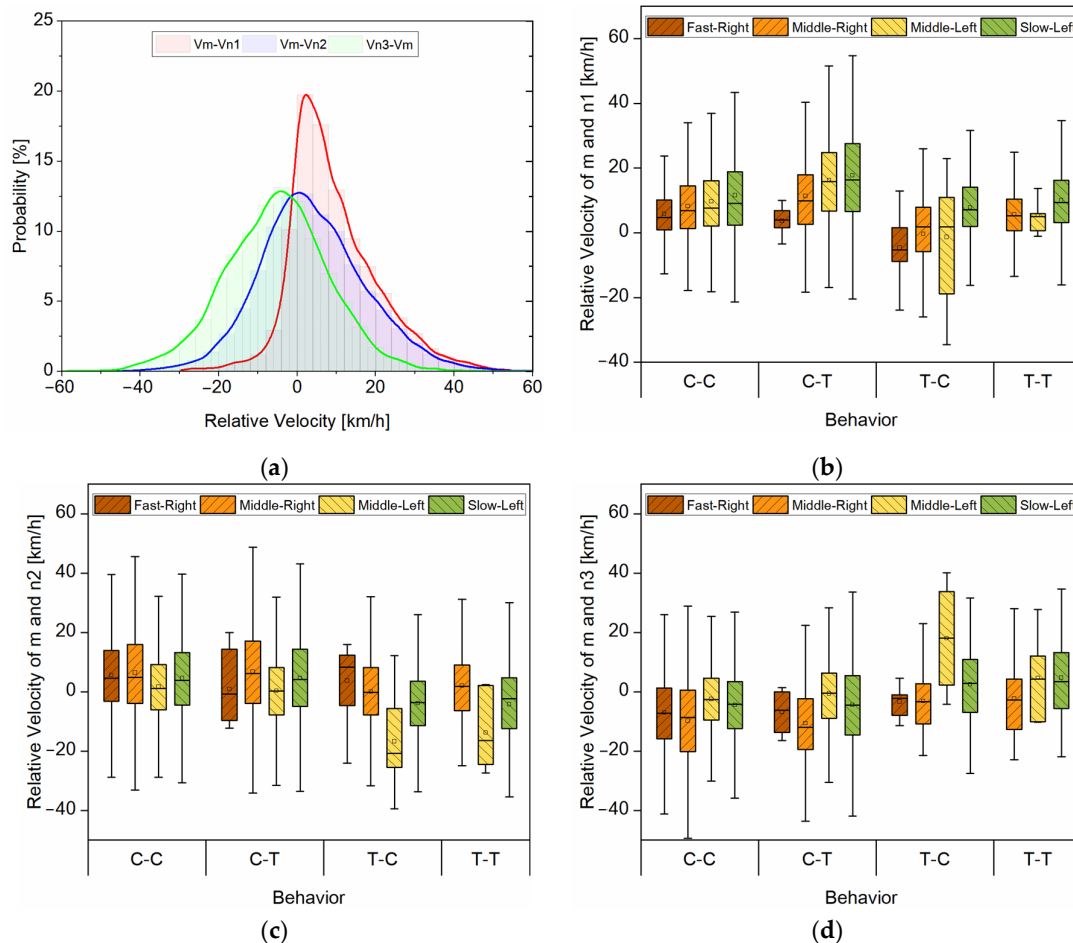


Figure 6. (a) Probability distribution of ΔV ; (b) ΔV between m and n1; (c) ΔV between m and n2; (d) ΔV between m and n3.

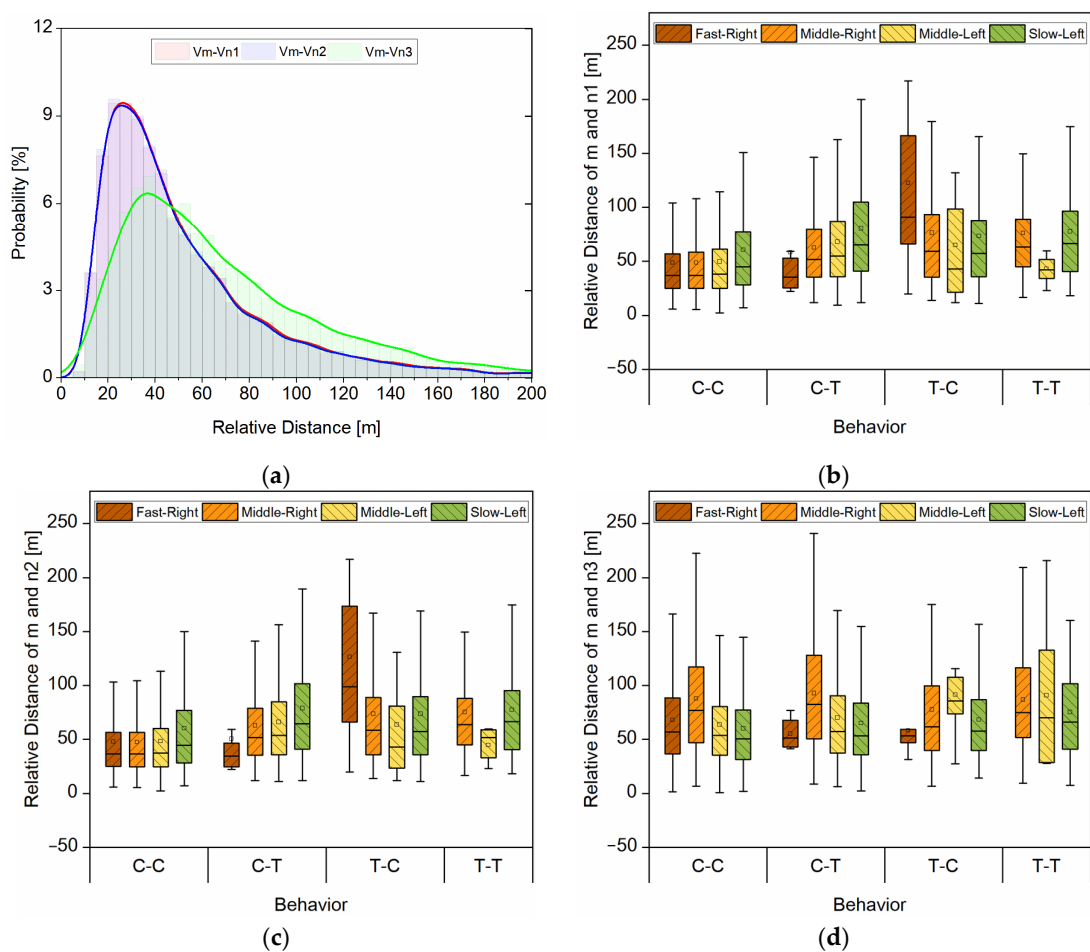
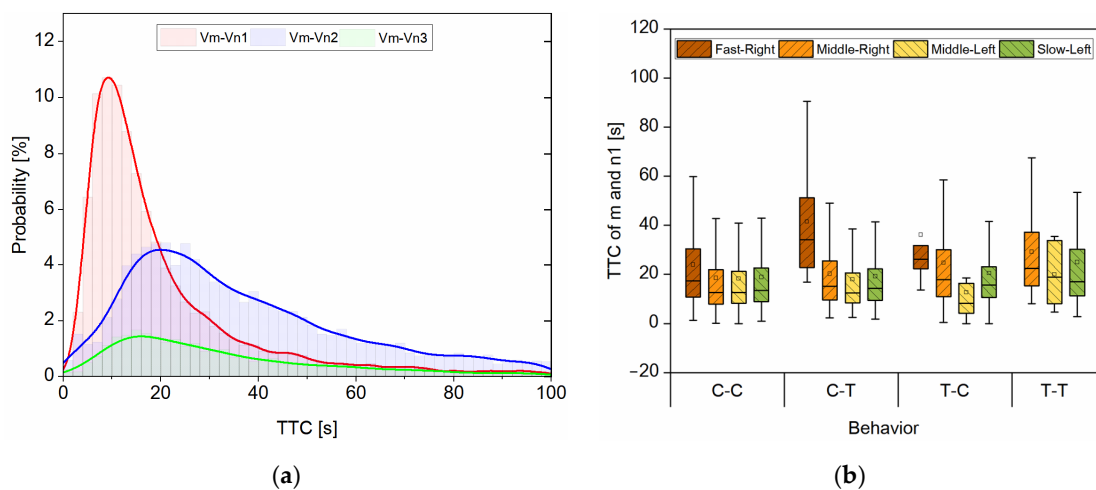


Figure 7. (a) Probability distribution of ΔD ; (b) ΔD between m and n1; (c) ΔD between m and n2; (d) ΔD between m and n3.



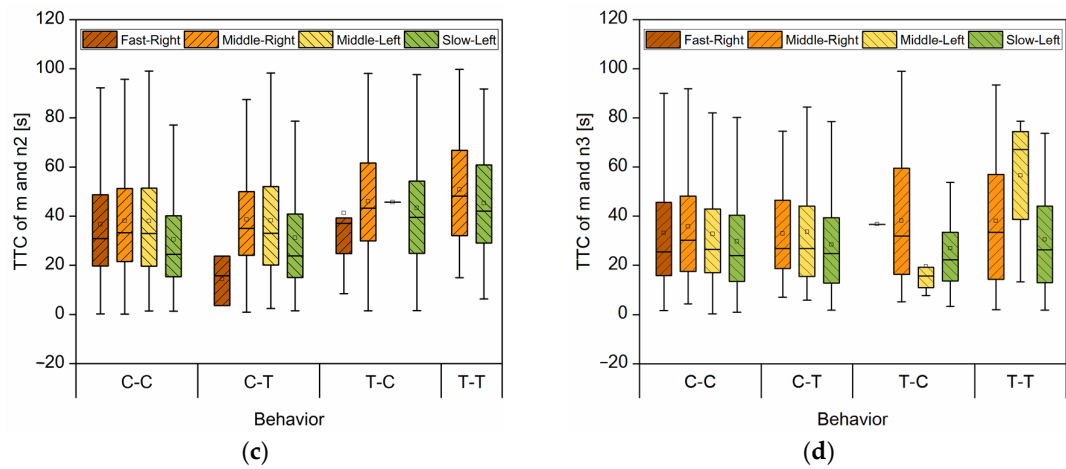


Figure 8. (a) Probability distribution of TTC; (b) TTC between m and n1; (c) TTC between m and n2; (d) TTC between m and n3.

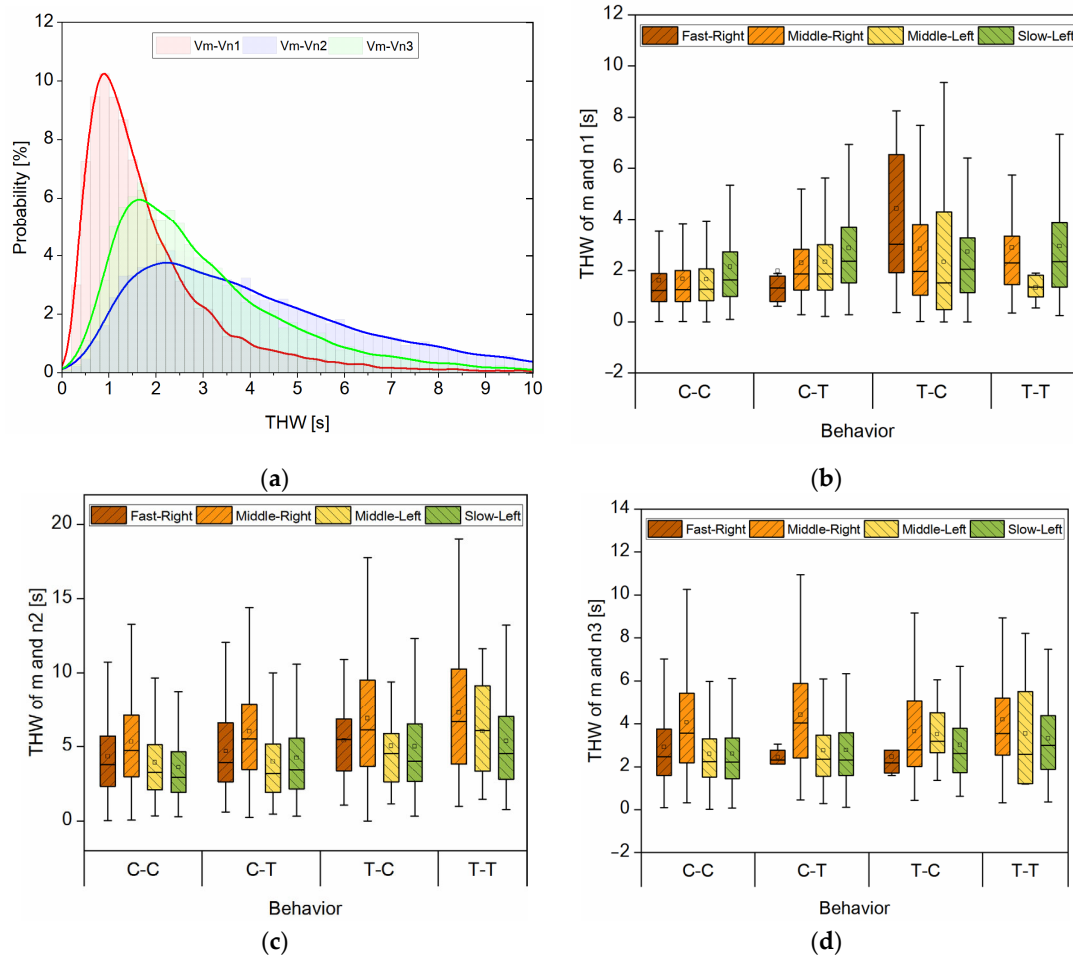


Figure 9. (a) Probability distribution of THW; (b) THW between m and n1; (c) THW between m and n2; (d) THW between m and n3.

Table 2. The mean and standard deviation of T_b of n3.

Combination	Fast-Right		Middle-Right		Middle-Left		Slow-Left	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C-C-C	1.30	0.83	1.25	0.84	1.23	0.79	1.19	0.80
C-T-C	1.16	0.68	1.23	0.68	0.80	0.35	1.22	0.80
T-C-C	-	-	1.32	0.60	-	-	1.58	1.34
T-T-C	-	-	0.93	0.48	-	-	1.61	0.58
C-C-T	1.06	0.55	1.48	0.81	-	-	1.42	0.87
C-T-T	1.33	0.63	1.50	0.61	-	-	1.48	1.39
T-C-T	-	-	0.91	0.35	-	-	-	-
T-T-T	-	-	1.20	0.27	-	-	1.66	0.83

Table 3. The mean and standard deviation of T_b of n5.

Combination	Fast-Right		Middle-Right		Middle-Left		Slow-Left	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C-C-C	1.32	0.82	1.41	0.90	1.28	0.86	1.42	0.88
C-T-C	1.72	1.20	1.64	1.06	1.16	0.36	1.12	0.76
T-C-C	-	-	1.77	0.85	-	-	1.51	0.95
T-T-C	-	-	1.66	-	-	-	1.78	1.15
C-C-T	1.09	0.59	1.09	0.57	-	-	1.29	1.04
C-T-T	1.50	0.22	1.61	0.40	-	-	3.03	1.36
T-C-T	-	-	1.49	0.41	-	-	-	-
T-T-T	-	-	1.18	0.36	-	-	1.66	0.43

Table 4. The mean and standard deviation of T_b difference between n3 and n5.

Combination	Fast-Right		Middle-Right		Middle-Left		Slow-Left	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C-C-C	0.01	1.02	0.15	1.12	0.05	1.12	0.22	1.09
C-T-C	0.55	1.23	0.41	1.29	0.36	0.15	-0.10	0.53
T-C-C	-	-	0.45	1.39	-	-	-0.06	1.64
T-T-C	-	-	0.73	-	-	-	0.16	0.56
C-C-T	0.03	0.81	-0.39	0.95	-	-	-0.12	1.33
C-T-T	0.17	0.59	0.11	0.21	-	-	1.55	0.02
T-C-T	-	-	0.57	0.50	-	-	-	-
T-T-T	-	-	-0.02	0.12	-	-	0.01	0.23

Table 5. The mean and standard deviation of T_a of n4.

Combination	Fast-Right		Middle-Right		Middle-Left		Slow-Left	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C-C-C	1.17	0.64	1.13	0.59	1.13	0.67	1.17	0.61
C-T-C	1.00	0.46	1.03	0.50	1.08	0.41	1.21	0.66
T-C-C	1.36	0.56	1.12	0.69	1.61	1.67	0.87	0.26
T-T-C	-	-	1.26	0.89	-	-	0.87	0.63
C-C-T	0.46	0.54	0.97	0.46	0.79	0.37	1.35	0.45
C-T-T	-	-	1.03	0.33	1.41	0.32	1.08	0.35
T-C-T	-	-	0.81	0.31	-	-	1.30	0.83
T-T-T	-	-	0.92	0.33	-	-	1.71	0.20

Table 6. The mean and standard deviation of T_a of n6.

Combination	Fast-Right		Middle-Right		Middle-Left		Slow-Left	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C-C-C	1.40	0.99	1.44	0.93	1.36	0.88	1.32	0.89
C-T-C	2.36	0.53	1.20	0.61	1.42	0.73	1.24	0.81
T-C-C	1.06	0.80	1.16	0.83	2.23	1.88	1.45	1.36
T-T-C	-	-	0.83	0.32	-	-	1.74	1.25
C-C-T	0.43	0.33	1.12	0.52	1.03	0.69	1.06	0.61
C-T-T			1.05	0.50	1.22	0.68	1.46	1.13
T-C-T	-	-	0.91	0.63	-	-	1.55	0.50
T-T-T	-	-	1.04	0.41	-	-	1.10	0.44

Table 7. The mean and standard deviation of T_a difference between n4 and n6.

Combination	Fast-Right		Middle-Right		Middle-Left		Slow-Left	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C-C-C	0.22	1.00	0.30	1.01	0.22	0.91	0.14	0.93
C-T-C	1.36	0.43	0.16	0.51	0.33	0.76	0.02	0.82
T-C-C	-0.30	0.23	0.04	0.88	0.61	0.21	0.58	1.45
T-T-C	-	-	-0.43	1.22	-	-	0.86	1.49
C-C-T	-0.03	0.17	0.15	0.63	0.23	0.68	-0.29	0.90
C-T-T			0.01	0.23	-0.18	0.66	0.38	0.77
T-C-T	-	-	0.10	0.70	-	-	0.25	0.47
T-T-T	-	-	0.12	0.44	-	-	-0.61	0.28

4. Discussion

Lane change times increased with the flowrate and density, while the largest amount was in the middle lane and the smallest in the fast lane. More lane change opportunities existed in the middle lane with the same traffic load, which resulted in more lane change times. Compared to German drivers, Chinese drivers showed slightly more lane changes with the same low flow rate and density and were significantly higher when the flow rate was larger than 1500 and density was larger than 15, which indicated that Chinese drivers drove more aggressively [24].

Car-Truck heterogeneous driving commonly existed in the middle and slow lanes, while heterogeneity was smaller in the fast lane. With the increase in truck portion, lane change times in the middle and slow lanes decreased and dropped more in the middle lane. This was similar to the trend in simulation research and provided data support for the simulation calibration [38]. It also indicated that the lane change intention decreased with the increase in traffic heterogeneity, especially for car drivers who were more willing to drive in low heterogeneous traffic. Research showed that similar traffic characteristics were found in the upper and lower roads if they were not congested, which is also found in this study, so the same lane in the upper and lower roads is considered as one in the following discussion [24].

Significant higher velocity was found for cars when changing from the right lane into the middle lane and higher when n1 was a car. It also existed for cars when left lane change in middle lane and illegally driving into fast lane was found for trucks. Velocity was lower for trucks, which affected the fluency of traffic. The velocity of cars in the slow lane was significantly higher than trucks, and it increased the potential driving risk. No matter which vehicle the m was, its velocity was significantly higher than others when changing from the right lane into the fast lane and lowered when changing from the left lane into the slow lane if n1 was cars. These can be explained by the speed limitation and the vehicle mixture in the middle lane. More aggressive behavior when right lane change happened

was found for cars in car–truck pair, considering the significant higher velocity in middle lane. They were even higher than the right lane change in fast lane.

Significant differences were found for ΔV_{m-n1} between various car follow types and lane change types. The relative velocity of the truck–car pair was significantly smaller than others when changing from the right lane into the fast lane and was less than zero. It indicated that trucks were not forced to change lanes due to the low speed of front cars but actively modified as the driver knew it was illegal. Relative velocity of car–truck pair was significantly higher than others, which showed lower endurance of low trucks speed for cars. No significant difference was found for relative velocity when m was truck. The relative velocity of the left lane change was higher than the right one, indicating a higher risk for the left lane change. It was also more dangerous in the slow lane as the relative velocity was higher than in the middle lane.

Significant differences were found for ΔV_{m-n2} between various car follow types and lane change types. The relative velocity of cars was significantly larger than trucks when changing from the right lane into the middle lane, indicating that cars drove more aggressively in the middle lane. Smaller ΔV_{m-n2} was found if V_m was truck, showing that trucks were more likely to consider the traffic fluency after lane changes. Left lane change in the middle lane of cars was more efficient due to the high driving speed and small relative velocity in the fast lane, which did not disturb the traffic. Trucks were slower than the front vehicle in the next lane when changing lanes at a maximum speed of 16 km/h, and it might influence the traffic speed. When changing from the left lane into the slow lane, cars drove faster than $n1$ and trucks slower, indicating that forward risk still existed for cars after the lane change. No matter what vehicle the $n2$ was, the relative velocity of trucks when left lane changing was larger, and that of cars was smaller than during right lane change, resulting from the driving behavior difference between cars and trucks.

It was found that many ego vehicles were slower than $n3$ at the lane change moment, introducing high backward driving risk, especially for trucks and left lane change. Significant differences were found for ΔV_{m-n3} between various car follow types and lane change types. There was a small backward risk for both vehicles when changing from the right lane into the middle lane due to the large relative velocity. They were smaller for cars with a significantly higher speed difference. The relative velocity of the truck–car pair was significantly higher than others when changing from the left lane. This might result in potential risk as it was illegal to drive in the fast lane. The relative velocity of trucks and $n3$ was higher than cars, and they were significantly slower than $n3$ when changing from the left lane into the slow lane, which also showed a potential backward risk. The significant difference was caused by m type rather than $n1$ type.

The mean values of ΔD_{m-n1} and ΔD_{m-n2} were closed, which was comparable with Ma et al. [39]. Significant differences were found for ΔD_{m-n1} between various car follow types and lane change types. The relative distance of trucks was significantly higher than cars when changing from the right lane into the fast lane, but it was more related to the illegal driving in the fast lane and the intention to drive back into the middle as soon as possible. The relative distance of the car–car pair was significantly smaller than the car–truck pair when right lane changing, indicating more aggressive behavior for cars when $n1$ is cars. This also related to the volume of truck and car driver would try to decrease the risk. Cars drove more aggressively than trucks, which is explained by the small relative distance. The relative distance of the car–truck pair was even higher than other combinations containing trucks when changing from the left lane. It meant that car drivers wanted to leave the slow lane as for the high risk coming from higher ego velocity and relative velocity when driving in the high truck portion lane. ΔD_{m-n1} was significantly small when cars were changing from the left lane changing than changing from the right one. The law did not restrict the right lane change maneuver but the right overpass maneuver in order to indirectly reduce this risk. The difference was not shown in trucks' lane changes.

A similar significant difference existed for ΔD_{m-n2} , which was also comparable with the former study [39]. Traffic efficiency was not improved as the vehicle block still existed after lane change, and the chaos might have increased due to frequent lane changes.

Significant differences were found for ΔD_{m-n3} between various car follow types and lane change types. A significantly higher relative distance was kept for cars when changing from the right lane into the middle lane, indicating that car drivers were more likely to keep a longer backward distance. A similar longer relative backward distance was found for trucks when changing from the left lane into the middle lane. Unlike cars, trucks are not able to accelerate too fast, so they will keep a greater distance in case of a collision when occupying the fast lane. Cars were usually driving in the fast and slow lanes, so they were more focused on the risks from the right-hand side, and the trucks would be focused on the left.

Similar significant differences were found for TTC_{m-n1} and THW_{m-n1} between various car follow types and lane change types. Cars were worried about the front trucks, indicated by the larger TTC_{m-n1} and THW_{m-n1} of the car–truck pairs, and a significant difference was not found when m was a truck. Right lane change in the fast lane was more dangerous since the TTC_{m-n1} and THW_{m-n1} were significantly small. Similar significant differences were found between various car follow types and lane change types. However, they were larger than that of m and $n1$, so even though the efficiency was not improved, drivers tended to evade the direct risk. Compared to the values of m and $n2$, TTC_{m-n3} and THW_{m-n3} were smaller, indicating that the backward risk cannot be ignored.

The break reaction time of cars was commonly faster than trucks, especially facing the vehicle cut-in changing from the right lane change into the fast lane. Reaction time was even shorter when facing trucks as for the higher alertness resulting from the high speed of the fast lane. It is distributed in [0.9, 1.67], which is similar to Japan [40] but smaller than the US [26], especially when changing from the right lane into the fast lane. This was related to the strict speed limitation regulation on the highway, with Chinese drivers tending to keep a small distance and are sensitive to the front behavior. It also indicated that Chinese drivers had a better reaction capability. Significant differences were not found between various car follow types. The $n5$ reacted slower than the $n3$, which might result from the concentration being put on the vehicle directly ahead. However, many $n5$ reacted close to $n3$, indicating that the cutting in by the vehicle was also focused, but the estimation was not precise, so it is a little delayed. For some sensitive drivers, they reacted even faster than $n3$.

The acceleration reaction time of $n4$ was faster when facing trucks, which might be related to the low speed of trucks. Cars tend to drive faster, and when the low-speed front vehicle left, they tried to accelerate aggressively. The acceleration reaction time was slightly faster than the break reaction time, which might result from the usage of pedals on the highway. Drivers' right feet were used to locate the gas pedal at high speed, so they needed extra time to transfer them to the break pedal when facing a cut-in, which can be neglected when facing a cut-out. The acceleration reaction time of $n6$ was longer than $n4$ due to the visual block of $n4$. However, it was less than the summary of two reaction times between every two vehicles in the three-vehicle platoon, which indicated that some of the drivers were able to focus on the front of the front vehicle.

When designing a good AD and ADAS system, the driving behavior in the target market should be considered thoroughly. In China, the driving speed was lower, and this led to higher heterogeneous traffic, which required a more alert driving policy for the autonomous driving system. Different system reactions should also be taken into account, as different behavior was shown when the lane change happened in various lanes and directions. To improve the fidelity of the system, it should learn to react differently when facing cars and trucks, as the drivers tend to change the lane earlier if the front vehicle is a truck. It should also be noted that the Chinese driver was more aggressive than the German.

This study provided basic driving behavior parameters, and it will be helpful in some bullet points for autonomous driving system designers. A Chinese driver model, which is necessary for the performance evaluation of the AD system according to the ALKS regulation, can be established using these data. Another suggestion is that different strategies can be developed when facing cars and trucks based on the data mentioned above in order to improve the comfort of the AD system.

5. Conclusions

This study investigated the typical Chinese driving behavior in the car–truck heterogeneous traffic. Results showed that a large difference existed in various car follow types and lane change types. The traffic was more steady in China when in fluent flow as the allowed driving speed was lower. With the increase in truck portion, lane change times in the middle and slow lanes decreased and dropped more in the middle lane. This will be used in the investigation of platoon driving behavior in heterogeneous traffic. Car drivers tended to drive left to the lane center, and truck drivers used to drive in the center. Cars drove more aggressively than trucks and showed a shorter reaction time. Cars would evade the dangerous situation when facing trucks by changing lanes at a longer relative distance. Smaller TTC and THW were found for trucks when facing cars. This will be helpful in the research about lane change behavior prediction and heterogeneous vehicular communication in the future. Differences were found between China and other countries, with more frequent lane-change maneuvers and shorter reaction times. Chinese drivers tend to keep a small distance and are sensitive to the front behavior with a better reaction capability, which is useful for the localization of AD and ADAS systems in intelligently connected vehicles in China.

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Appendix A

Table A1. The mean and standard deviation of m velocity.

Combination	Fast-Right		Middle-Right		Middle-Left		Slow-Left	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C-C	94.81	13.39	92.56	14.05	93.10	14.52	90.03	15.36
C-T	92.11	7.90	90.01	13.63	94.06	13.78	91.13	15.63
T-C	90.97	8.35	83.13	10.28	81.14	11.51	79.86	11.38
T-T	-	-	79.99	9.96	83.19	8.07	78.89	10.46

Note: (1) Significant difference existed between lane change type 1 and 2, 3, 4, and 4 and 2, 3 for car-car; (2) Significant difference existed between lane change type 3 and 2, 4 for car-truck; (3) Significant difference existed between lane change type 1 and 2, 3, 4 for truck-car; (4) Significant difference not existed between lane change type for truck-truck; (5) Significant difference not existed between car follow types for right change in fast lane; (6) Significant difference existed between all car follow types for right change in middle lane; (7) Significant difference existed between car follow type 3 and 1, 2 for left change in middle lane. (8) Significant difference existed between car follow type 1 and 3, 4 and 2 and 3, 4 for left change in slow lane.

Table A2. The mean and standard deviation of ΔV of m and n1.

Combination	Fast-Right		Middle-Right		Middle-Left		Slow-Left	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C-C	5.87	8.16	8.23	10.82	9.70	10.79	11.61	12.84
C-T	3.66	4.34	11.41	11.39	16.29	11.81	17.73	13.70
T-C	-4.59	9.80	-0.31	13.35	-1.31	17.48	7.81	11.09
T-T	-	-	5.69	8.37	5.45	5.90	9.98	9.41

Note: (1) Significant difference existed between all lane change types for car-car; (2) Significant difference existed between lane change type 1 and 3, 4 and 2 and 3, 4 for car-truck; (3) Significant difference existed between lane change type 4 and 1, 4 for truck-car; (4) Significant difference existed between lane change type 2 and 4 for truck-truck; (5) Significant difference existed between car follow type 3 and 1, 4 for right change in fast lane; (6) Significant difference existed between all car follow types for right change in middle lane; (7) Significant difference existed between car follow type 2 and 1, 3, 4 for left change in middle lane; (8) Significant difference existed between car follow type 1 and 3, and 2 and 1, 3, 4 for left change in slow lane.

Table A3. The mean and standard deviation of ΔV of m and n2.

Combination	Fast-Right		Middle-Right		Middle-Left		Slow-Left	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C-C	5.65	12.95	6.40	15.00	1.76	11.95	4.57	13.77
C-T	0.8508	11.51	6.81	15.40	0.35	12.44	4.58	15.19
T-C	3.71	12.15	0.02	12.94	-16.77	13.67	-3.86	12.21
T-T	-	-	2.05	11.59	-13.80	11.81	-4.18	13.22

Note: (1) Significant difference existed between lane change type 3 and 1, 3, 4, and 4 and 1, 2 for car-car; (2) Significant difference existed between lane change type 3 and 2, 4 for car-truck; (3) Significant difference existed between lane change type 3 and 1, 2, 4 and 4 and 1, 2 for truck-car; (4) Significant difference existed between lane change type 2 and 3, 4 for truck-truck; (5) Significant difference not existed between car follow types for right change in fast lane; (6) Significant difference existed between all car follow type1 and 3, 4 and 2 and 3, 4 for right change in middle lane; (7) Significant difference existed between car follow type 1 and 2, 3, 4 and 2 and 3 for left change in middle lane.; (8) Significant difference existed between car follow type 2 and 3 for left change in slow lane.

Table A4. The mean and standard deviation of ΔV of m and n3.

Combination	Fast-Right		Middle-Right		Middle-Left		Slow-Left	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C-C	-7.01	13.00	-9.78	15.11	-2.46	10.93	-4.41	12.43
C-T	-6.84	8.25	-10.62	14.20	-0.63	11.96	-4.42	14.10
T-C	-3.39	5.60	-3.11	10.71	18.03	17.17	2.48	12.09
T-T	-	-	-2.32	12.21	4.64	14.41	4.73	13.44

Note: (1) Significant difference existed between all lane change types for car-car; (2) Significant difference existed between lane change type 2 and 3, 4 and 3 and 4 for car-truck; (3) Significant difference existed between lane change type 2 and 3, 4 for truck-car; (4) Significant difference existed between lane change type 2 and 4 for truck-truck; (5) Significant difference not existed between car follow types for right change in fast lane; (6) Significant difference existed between car follow type 1 and 3, 4 and 2 and 3, 4 for right change in middle lane; (7) Significant difference existed between car follow type 1 and 3, 4 and 2 and 3 for left change in middle lane. (8) Significant difference existed between car follow type 1 and 3, 4 and 2 and 3, 4 for left change in slow lane.

Table A5. The mean and standard deviation of ΔD of m and n1.

Combination	Fast-Right		Middle-Right		Middle-Left		Slow-Left	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C-C	48.62	40.41	48.62	38.49	49.63	39.15	60.61	48.78
C-T	58.18	57.22	62.83	41.11	68.15	47.58	80.44	56.15
T-C	122.69	86.47	76.44	58.27	64.99	55.78	73.54	57.68
T-T	-	-	76.17	51.55	43.22	12.92	77.65	51.19

Note: (1) Significant difference existed between lane change type 4 and 1, 2, 3 for car-car; (2) Significant difference existed between lane change type 4 and 2, 3 for car-truck; (3) Significant difference existed between lane change type 1 and 2, 3, 4 for truck-car; (4) Significant difference not existed between lane change type for truck-truck; (5) Significant difference existed between car follow type 3 and 1, 2 for right change in fast lane; (6) Significant difference existed between car follow type 1 and 2, 3, 4 and 2 and 4 for right change in middle lane; (7) Significant difference existed between car follow type 1 and 2 for left change in middle lane. (8) Significant difference existed between car follow type 1 and 2, 3, 4 and 2 and 4 for left change in slow lane.

Table A6. The mean and standard deviation of ΔD of m and n2.

Combination	Fast-Right		Middle-Right		Middle-Left		Slow-Left	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C-C	47.98	39.22	47.44	37.10	48.35	36.98	60.32	48.82
C-T	50.49	53.13	62.91	41.36	66.10	44.90	78.83	53.75
T-C	126.59	87.74	73.63	54.63	63.61	55.66	73.63	56.48
T-T	-	-	75.21	50.21	44.68	14.36	77.58	51.72

Note: (1) Significant difference existed between lane change type 4 and 1, 2, 3 for car-car; (2) Significant difference existed between lane change type 4 and 1, 2, 3 for car-truck; (3) Significant difference existed between lane change type 1 and 2, 3, 4 for truck-car; (4) Significant difference not existed between lane change type for truck-truck; (5) Significant difference existed between car follow type 3 and 1, 2 for right change in fast lane; (6) Significant difference existed between car follow type 1 and 2, 3, 4 and 2 and 4 for right change in middle lane; (7) Significant difference existed between car follow type 1 and 2 for left change in middle lane; (8) Significant difference existed between car follow type 1 and 2, 3, 4 and 2 and 4 for left change in slow lane.

Table A7. The mean and standard deviation of ΔD of m and n3.

Combination	Fast-Right		Middle-Right		Middle-Left		Slow-Left	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C-C	67.97	42.59	87.91	53.08	63.59	40.28	60.05	38.89
C-T	55.29	16.18	92.90	57.20	70.09	45.36	65.07	41.49
T-C	58.45	25.46	77.64	49.18	91.33	40.77	68.27	44.00
T-T	-	-	86.82	50.69	90.85	75.06	75.19	45.36

Note: (1) Significant difference existed between all lane change types for car-car; (2) Significant difference existed between lane change type 2 and 3, 4 for car-truck; (3) Significant difference not existed between lane change types for truck-car; (4) Significant difference not existed between lane change types for truck-truck; (5) Significant difference not existed between car follow types for right change in fast lane; (6) Significant difference existed between car follow types 2 and 3 for right change in middle lane; (7) Significant difference existed between car follow type 1 and 2 for left change in middle lane. (8) Significant difference existed between car follow type 1 and 4 for left change in slow lane.

Table A8. The mean and standard deviation of TTC of m and n1.

Combination	Fast-Right		Middle-Right		Middle-Left		Slow-Left	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C-C	23.98	19.40	18.53	17.23	18.31	16.45	18.88	15.89
C-T	41.49	24.33	20.25	15.98	17.96	16.03	19.27	15.97
T-C	36.18	29.12	24.77	20.83	12.70	12.86	20.55	16.46
T-T	-	-	29.22	19.51	20.01	13.29	24.98	20.17

Note: (1) Significant difference existed between lane change type 1 and 2, 3, 4, and 4 and 2, 3 for car-car; (2) Significant difference existed between lane change type 1 and 2, 3, 4 and 2 and 3 for car-truck; (3) Significant difference existed between lane change type 3 and 1, 2 for truck-car; (4) Significant difference not existed between lane change type for truck-truck; (5) Significant difference existed between car follow type 1 and 2 for right change in fast lane; (6) Significant difference existed between all car follow types for right change in middle lane; (7) Significant difference not existed between car follow types for left change in middle lane; (8) Significant difference existed between car follow type 1 and 3, 4 and 2 and 4 for left change in slow lane.

Table A9. The mean and standard deviation of TTC of m and n2.

Combination	Fast-Right		Middle-Right		Middle-Left		Slow-Left	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C-C	36.66	22.43	38.10	22.20	38.00	23.03	30.48	20.46
C-T	14.37	10.12	38.65	21.23	38.27	22.86	31.21	22.17
T-C	41.23	28.83	46.02	22.81	45.72	-	43.34	21.83
T-T	-	-	50.82	23.68	-	-	45.26	21.94

Note: (1) Significant difference existed between lane change type 1 and 2, and 4 and 1, 2, 3 for car-car; (2) Significant difference existed between lane change type 4 and 2, 3 for car-truck; (3) Significant difference not existed between lane change types for truck-car; (4) Significant difference not existed between lane change type for truck-truck; (5) Significant difference not existed between car follow types for right change in fast lane; (6) Significant difference existed between all car follow types for right change 1 and 3, 4 and 2 and 3, 4 right change in middle lane; (7) Significant difference not existed between car follow types for left change in middle lane. (8) Significant difference existed between car follow type 1 and 3, 4 and 2 and 3, 4 for left change in slow lane.

Table A10. The mean and standard deviation of TTC of m and n3.

Combination	Fast-Right		Middle-Right		Middle-Left		Slow-Left	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C-C	33.19	23.51	35.79	22.71	32.77	21.57	29.75	20.97
C-T	-	-	32.97	20.92	33.62	22.31	28.49	19.00
T-C	36.77	-	38.21	26.02	19.68	14.71	26.95	18.12
T-T	-	-	38.13	24.72	56.58	29.44	30.50	20.75

Note: (1) Significant difference existed between lane change type 2 and 4 for car-car; (2) Significant difference not existed between lane change types for car-truck; (3) Significant difference not existed between lane change types for truck-car; (4) Significant difference not existed between lane change types for truck-truck; (5) Significant difference not existed between car follow types for right change in fast lane; (6) Significant difference not existed between car follow types for right change in middle lane; (7) Significant difference not existed between car follow types for left change in middle lane; (8) Significant difference not existed between car follow types for left change in slow lane.

Table A11. The mean and standard deviation of THW of m and n1.

Combination	Fast-Right		Middle-Right		Middle-Left		Slow-Left	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C-C	1.62	1.44	1.67	1.47	1.66	1.35	2.15	1.82
C-T	1.99	2.01	2.30	1.63	2.34	1.65	2.88	1.99
T-C	4.42	3.51	2.85	2.70	2.34	2.40	2.74	2.59
T-T	-	-	2.90	2.45	1.34	0.50	2.96	2.25

Note: (1) Significant difference existed between lane change type 1 and 3, and 4 and 1, 2, 3 for car-car; (2) Significant difference existed between lane change type 4 and 1, 2, 3 for car-truck; (3) Significant difference not existed between lane change type for truck-car; (4) Significant difference existed between lane change type 3 and 2, 3 for truck-truck; (5) Significant difference existed between car follow type 1 and 3 for right change in fast lane; (6) Significant difference existed between car follow type 1 and 2, 3, 4 and 4 and 2, 3 for right change in middle lane; (7) Significant difference existed between car follow type 1 and 2 for left change in middle lane; (8) Significant difference existed between car follow type 1 and 2, 3, 4 and 3 and 2, 4 for left change in slow lane.

Table A12. The mean and standard deviation of THW of m and n2.

Combination	Fast-Right		Middle-Right		Middle-Left		Slow-Left	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C-C	4.32	2.68	5.31	3.14	3.92	2.54	3.59	2.45
C-T	4.67	3.22	6.00	3.42	3.97	2.78	4.23	3.01
T-C	5.38	2.64	6.88	4.06	5.03	3.31	5.00	3.31
T-T	-	-	7.28	4.20	6.00	3.58	5.36	3.40

Note: (1) Significant difference existed between all lane change types for car-car; (2) Significant difference existed between lane change type 2 and 3, 4 for car-truck; (3) Significant difference existed between lane change type 2 and 4 for truck-car; (4) Significant difference existed between lane change type 2 and 4 for truck-truck; (5) Significant difference not existed between car follow types for right change in fast lane; (6) Significant difference existed between car follow type 1 and 2, 3, 4 and 2 and 4 for right change in middle lane; (7) Significant difference not existed between car follow types for left change in middle lane; (8) Significant difference existed between car follow type 1 and 2, 3, 4 and 2 and 3, 4 for left change in slow lane.

Table A13. The mean and standard deviation of THW of m and n3.

Combination	Fast-Right		Middle-Right		Middle-Left		Slow-Left	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C-C	2.91	1.80	4.06	2.44	2.59	1.52	2.60	1.62
C-T	2.45	0.43	4.41	2.65	2.76	1.65	2.77	1.71
T-C	2.46	1.02	3.65	2.22	3.51	1.51	3.01	1.87
T-T	-	-	4.20	2.45	3.54	2.85	3.32	1.94

Note: (1) Significant difference existed between lane change type 1 and 3, 4, and 2 and 1, 3, 4 for car-car; (2) Significant difference existed between lane change type 2 and 3, 4 for car-truck; (3) Significant difference not existed between lane change types for truck-car; (4) Significant difference existed between lane change type 2 and 4 for truck-truck; (5) Significant difference not existed between car follow types for right change in fast lane; (6) Significant difference existed between car follow type 2 and 3 for right change in middle lane; (7) Significant difference not existed between car follow types for left change in middle lane; (8) Significant difference existed between car follow type 1 and 3, 4 and 2 and 4 for left change in slow lane.

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