2018 IEEE Intelligent Vehicles Symposium (IV)
Changshu, Suzhou, China, June 26-30, 2018

The Relationship between Different Safety Indicators in Car-following Situations

Tong Liu, Selpi, and Rui Fu

***Abstract*— Studying different aspects of car-following behavior is still of strong interests for many researchers, due to its usefulness in many applications, such as for further development of traffic simulators and active safety systems (e.g., Adaptive Cruise Control and Autonomous Emergency Braking). This paper investigates the relationships between several safety indicators (e.g., time gap, gap distance, time to collision) in car-following situations, and analyzes which of these indicators affect driver's behavior in car-following situations and how. All analyses are done using real driving data collected in China. The paper also suggests parameters that can be used for defining, identifying, and extracting car-following events from real driving data. Results indicate that time gap is less sensitive to the variations in speed and road condition compared with gap distance in this test. TTC in the low speed range of subject-vehicle is found to be steady compared with other speed ranges, so is the time gap in the high speed range. Therefore, time gap is more suitable to be the safety indicator compared with gap distance in the future car-following research. Time gap is found to be more appropriate for the analysis of car following behavior in the high speed ranges, but both TTC and time gap should be used as part of the safety indicator for the low speed ranges.**

I. INTRODUCTION

Research on car-following behavior have drawn ever increasing attention from all over the world since 1960s [1]. This is partly because of the usefulness of car-following behavior for many applications. It can be used for further development of Adaptive Cruise Control (ACC) and Autonomous Emergency Braking (AEB). The driving style aspect of car-following behavior could also be used by manufacturers to develop a personalized active safety systems, as well as systems that work worldwide (i.e., took into account local traffic culture, etc.). Beside active safety systems, such knowledge could also be used for further development of traffic simulators.

The purpose of this paper is to investigate the relationship between several safety indicators (e.g., time gap, gap distance, time to collision, speed, etc.) in car-following situations, and identify which of these indicators affect driver's speed control and how. In doing so, we also discuss definition and extraction of car-following events from real driving data.

Though car-following concept is widely understood among the researchers, there is no exact definition that can be used as a standard way of identifying car-following situations or events from a set of driving data. To identify a car-following situation, the first thing is to identify the lead vehicle on the same lane with the subject vehicle. Zhu et al. [7] used lateral distance ranging from -2.5 to 2.5 meters to decide if the lead vehicle and subject vehicle were running in the same lane, but it is generally very difficult to get lateral distance of the lead vehicle directly from the sensors in the subject vehicle.

Once the lead vehicle on the same lane has been identified, we need to differentiate car-following situation from a free-flow situation. Different ways have been used in the literatures. The results of a field observation in Sweden [4] suggested time headway (THW) of 6 seconds was optimal for distinguishing between car-following and free-flow condition. However, THW less than 3 seconds was accepted to define a car-following event in the American Association for State Highway Transportation Officials (AASHTO) Highway Capacity Manual [2], and the same threshold was also used in [3], yet no theoretical foundation was provided for this value. Besides using time-related measure, distance has also been used. In [16], one of the criteria used was "the lead vehicle is within 120 meters" on the same lane with the subject vehicle. Though it was not clearly specified, we think this 120-meters distance refers to the gap distance (from front bumper of the subject vehicle to the back bumper of the lead vehicle), rather than headway distance (which is gap distance plus the length of the lead vehicle), particularly because the data used in [16] has radar range that measures gap distance to detected objects.

Once car-following situations are identified, many analyses can be done. Different authors, in the past, have focused on different safety indicators to analyze the car-following situations. For example, time gap and gap distance were used in [5], time to collision (TTC), time headway and "safety margin" (a combination of TTC and time headway) were used in [6], while others suggested using time headway for the longer distance car-following situations and distance headway for the shorter distance situations such as urban roads [4]. In this study, we use several safety indicators and analyze the relationships between them, in a bid to identify which of these indicators affect driver's behavior in car-following situations and how.

II. METHODS

A. Data

The dataset used here was collected using an instrumented vehicle in real traffic between Huzhou and Changxing in Zhejiang province, China. The dataset consists of 650 kilometers of driving from 12 male driving school instructors of age group 36 to 50 years old. The average driving experience of the participants was 21.2 years with a standard deviation of 4.8 years. All of the participants were

Tong Liu is with the School of Automobile, Chang'an University, Xi'an *710064*, China (phone: +86-18292803558; e-mail: liutong@chd.edu.cn).
Selpi is with the Division of Vehicle Safety, Department of Mechanics and Maritime Sciences, Chalmers University of Technology, Gothenburg SE-*412 96*, Sweden (e-mail: selpi@chalmers.se).
Rui Fu is with the Key Laboratory of Automotive Transportation Safety Technology, Ministry of Transport, PRC, Chang'an University, Xi'an *710064*, China (e-mail: furui@chd.edu.cn).

asked to drive as they usually do in their everyday driving. The test session lasted for 70-90 minutes for each participant. They were mainly driving on two different kinds of test routes: national highway 104 and expressway G25, with the speed limit ranging from 70 to 90 km/h and 110 km/h, respectively (see Fig. 1). Furthermore, traffic jam and congested roads are rarely existed in the whole driving sessions, only several traffic lights and crossroads on the national highway.

Fig. 1 Car-following scenarios in two kinds of test routes

In this test, the data such as relative angle to nearby objects, gap distance (distance from the front bumper of the subject vehicle to the back bumper of the lead vehicle) and relative speed to the lead vehicle were collected by millimeter-wave radar, with the range of 174 meters, field angle of +/-10 degrees and update grade of 50 milliseconds. The speed of the subject vehicle was extracted from CAN-bus. Six cameras were installed in the instrumented vehicle to record the front view, rear view, two side views, driver's face and pedal area. The videos were used to verify uncertain car-following events. Other data like time gap (time from the front bumper of the subject vehicle to the back bumper of the lead vehicle) and TTC were calculated. All of the data used for car-following analysis were recorded at 10 Hz here.

B. Extraction of Car-Following Events

In our case, the radar in the instrumented vehicle could record 64 objects at the same time. We distinguish the lead vehicle in the same lane from the 64 objects detected by the radar by using absolute value of relative angle with the detected object up to 2 degrees.

Once the lead vehicle is identified, car-following events were then identified with the following criteria: speed of subject vehicle is above 10 km/h, and (gap distance is up to 120 meters or time gap is up to 6 seconds). The data surrounding the start and the stop of the identified events were checked. Those that are considered to be naturally part of the identified events though they have absolute values of relative angle with the lead vehicle greater than 2 degrees were included as part of the events. In such cases, the start and/or stop of the affected events were extended manually. 530 car-following events were gathered in total.

Considering the size of the data used here and the purpose of this study, we deliberately chose more generous thresholds (i.e., not to miss car-following events). The threshold used for vehicle speed can definitely be set higher, as most other papers, for example 18 km/h can be used to avoid including traffic jam. The threshold for gap distance is set following [16]. Considering that the optimum time headway to distinguish car-following and free-flow situations was found to be 6 seconds in [4], the time gap could be set lower than 6 seconds. The distribution of gap distance and relative angle from one driver with rules mentioned above was shown in Fig. 2.

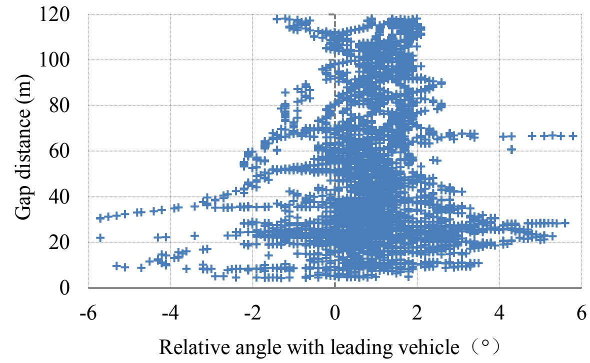


Fig. 2 Car-following data from one driver

III. Results

A. Distribution of Parameters

Fig. 3 presented the frequency and cumulative frequency in different gap distance ranges for 12 professional drivers during the whole driving process. All car-following data was grouped according to the distance range, the data with gap distance between 0 and 10 meters (included) fell into group with a distance of 10 meters, the data with gap distance between 10 (excluded) and 20 meters (included) fell into group with a distance of 20 meters, and so on. The mean and median values for the gap distance were 42.7 meters and 36.7 meters, respectively. The peak value of gap distance frequency appeared at the range of 20 meters to 30 meters, which indicates that the drivers were more inclined to drive in a range of that magnitude among car-following situations. For the range of gap distance greater than that, the frequencies decreased gradually.

Likewise, the frequency and cumulative frequency in different ranges of time gap were shown in Fig. 4. Here, the data with time gap between 0 and 0.5 seconds (included) fell into group of 0.5 seconds, the data with time gap between 0.5 (excluded) and 1.0 seconds (included) fell into group of 1.0 seconds, and so on. The mean and median values for the average time gap were 2.21 seconds and 1.99 seconds, respectively. The peak value of time gap frequency appeared

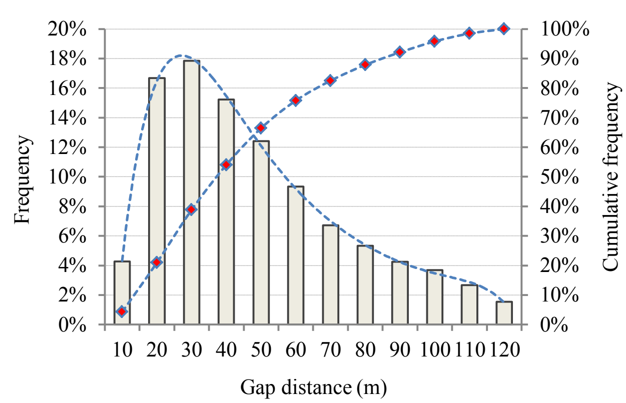


Fig. 3 The distribution of gap distance for 12 professional drivers

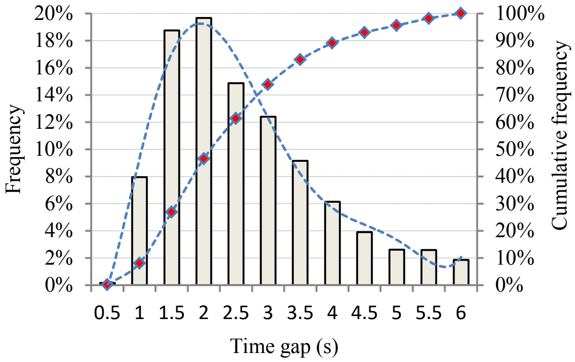


Fig. 4 The distribution of time gap for 12 professional drivers

at the range of 1.5 seconds to 2.0 seconds, after this range, the frequency of time gap began to decrease gradually.

From Fig. 3 and Fig. 4, one could see that the time gap distribution was very similar to that of the gap distance distribution. Moreover, the graphs of gap distance and time gap were positively skewed, having a longer 'tail' on the right side, for both graphs.

B. Comparison of Average Gap Distance and Time Gap among Events

In this part, we compared with the results of average gap distance and average time gap of each car-following event. The relationships between average speed of the subject vehicle and other factors such as average gap distance and time gap among all of the car-following events were plotted in Fig. 5 and Fig. 6. One could see that the values of average gap distance increase along with the increase of average speed (significance level of test $p < .01$, coefficient of correlation $r=0.63$). However, the values of average time gap nearly have no correlation with average speed ($p < .01$, $r=0.12$). These suggest that drivers tend to keep longer distance when driving in higher speed generally ($r=0.63$), but driver may use a similar range of time gap values regardless of their average speed ($r=0.12$).

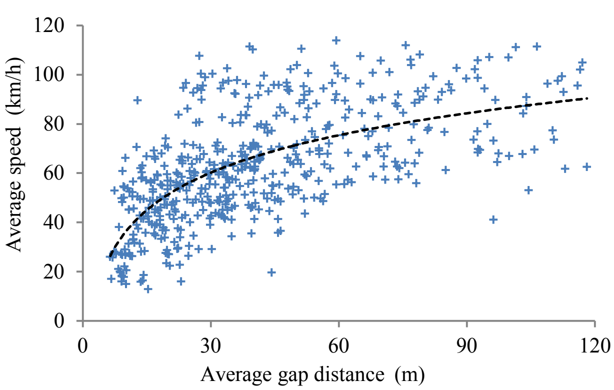


Fig. 5 The distribution of average gap distance among events

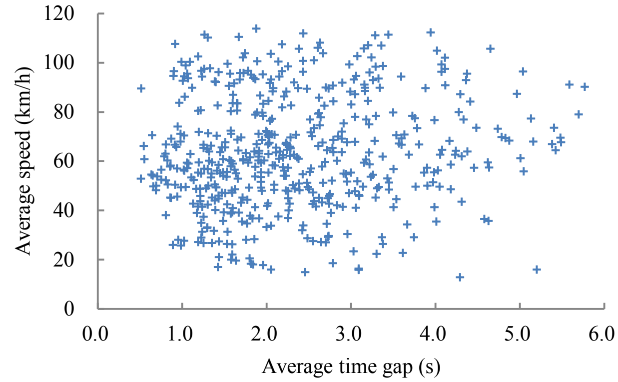


Fig. 6 The distribution of average time gap among events

C. Comparison of Gap Distance and Time Gap in Different Speed limits

Since average gap distance of each event increased with average speed basically and average time gap of each event was not affected by average speed in this test, what about the relationship of gap distance and time gap for all of the car-following data? Actually, for different speed limits, the gap distance and time gap also showed the same tendency here, as shown in Fig. 7 and Fig. 8.

To test the influence of the subject vehicle speed in different speed limits on gap distance and time gap, two one-way analysis of variance (ANOVA) were performed, with factors of speed limits (70 km/h, 90 km/h, 110 km/h),

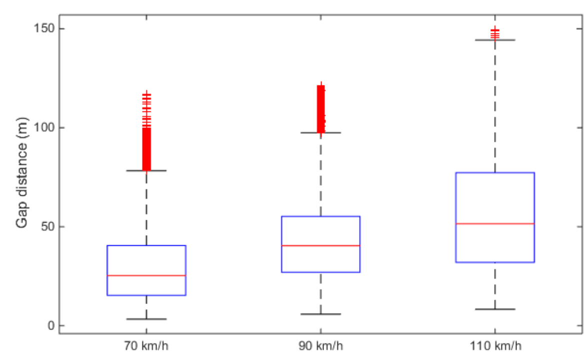


Fig. 7 The distribution of gap distance in different speed limits

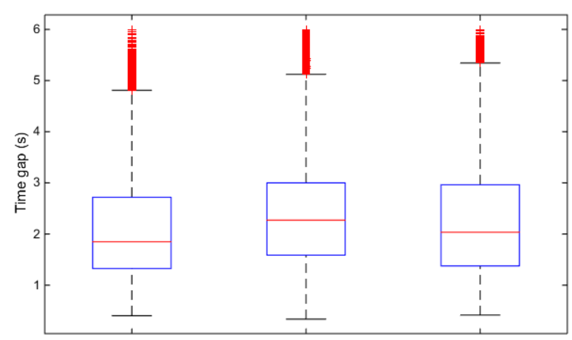


Fig. 8 The distribution of time gap in different speed limits

with dependent variable of distance gap and time gap, respectively.

The values of average gap distance expressed in meters (m) are 30.37 m (standard deviation SD=18.98) in the speed limit of 70 km/h condition, 43.39 m (SD=22.66) in the speed limit of 90 km/h condition, and 55.94 m (SD=28.31) in the speed limit of 110 km/h condition. Likewise, the values of average time gap expressed in seconds (s) are 2.11 s (SD=1.03) in the speed limit of 70 km/h condition, 2.42 s (SD=1.12) in the speed limit of 90 km/h condition, and 2.24 s (SD=1.05) in the speed limit of 110 km/h condition.

We found that there were significant influence of the subject vehicle speed in different speed limits on the gap distance (F-statistics value F=12487.9, $p < .01$) and time gap (F=546.3, $p < .01$). However, the values of average time gap in different speed limits are all located between 2.0 and 2.5 s. In addition, it was observed that the spread of gap distance was bigger at high speed compared to that at low speed, while the spread of time gap was similar in different speed limit conditions.

Furthermore, to show the tendency and compare with each other more clearly, the cumulative frequency of gap distance and time gap in different speed limits were also presented in Fig. 9 and Fig. 10.

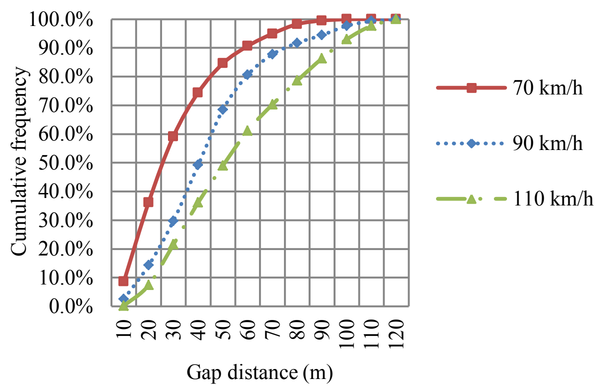


Fig. 9 The cumulative frequency of gap distance in different speed limits

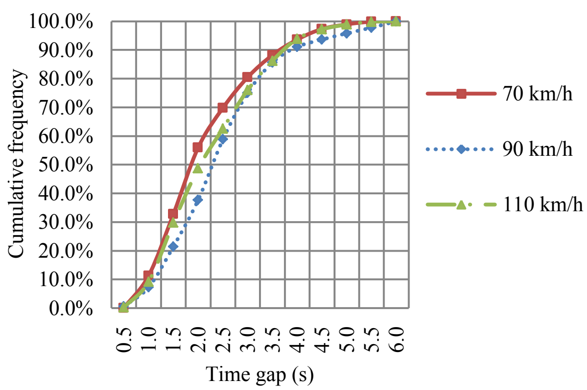


Fig. 10 The cumulative frequency of time gap in different speed limits

D. Comparison of Gap Distance and Time Gap on Different Roads

As mentioned before, there were two kinds of routes here: national highway 104 (speed limit ranging from 70 to 90 km/h) and expressway G25 (speed limit 110 km/h). The distribution of gap distance and time gap on the national highway and expressway are shown in Fig. 11 and Fig. 12. In this case, we found that it was also in line with the tendency in Fig. 7 and Fig. 8, which was helpful to understand the car-following behaviors from different perspectives.

To test the influence of different road conditions on gap distance and time gap, two one-way ANOVA were also performed here. The values of average gap distance are 33.70 m (SD=20.78) on the national highway, and 55.94 m (SD=28.31) on the expressway. Similarly, the values of average time gap are 2.19 s (SD=1.06) on the national highway, and 2.24 s (SD=1.05) on the expressway.

There were also significant influence of the road conditions on the gap distance (F=20779.3, $p < .01$) and time gap (F=55.35, $p < .01$). However, the values of average time gap on different roads are all around 2.2 s. Furthermore, it was also observed that the spread of gap distance was much bigger on the expressway compared to that on the national highway, while the spread of time gap was still similar on different road conditions.

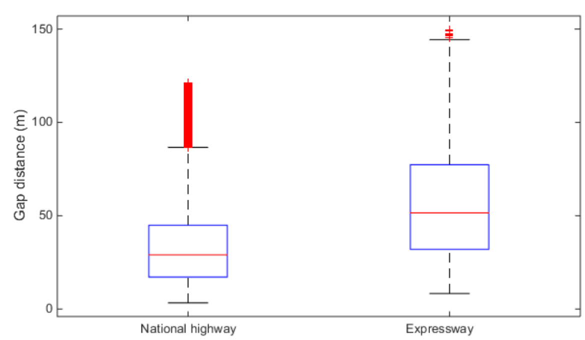


Fig. 11 The distribution of gap distance on different roads

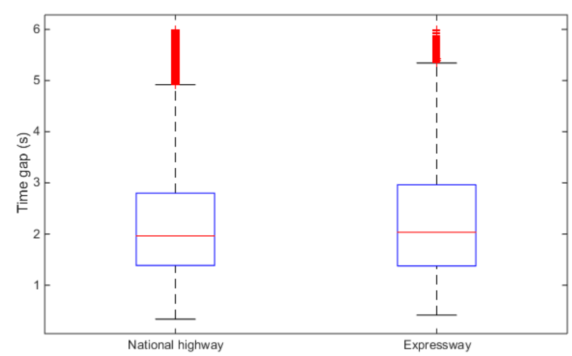


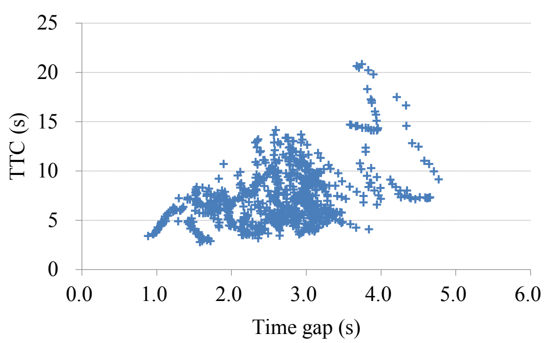
Fig. 12 The distribution of time gap on different roads

E. Comparison of Time Gap and TTC in Different Relative Speed Ranges and Subject-vehicle Speed Ranges

In this subsection, the relationship between time gap and TTC in different relative speed ranges and subject-vehicle speed ranges were analyzed. Here, relative speed is defined as $\Delta V = V_{subject\_vehicle} - V_{lead\_vehicle}$.

When TTC was plotted against time gap, it was found that the correlation between TTC and time gap increases as the subject-vehicle speed range increases (Fig. 13). When TTC and time gap were plotted separately against the relative speed (Fig. 14 and Fig.15), it was found that at low relative speed (5-10 km/h), the values of average time gap for the different subject-vehicle speed ranges are pretty similar, and the difference of average time gap values for the different subject-vehicle speed ranges increases as the relative speed range increases. And it was the opposite for TTC (i.e., at low relative speed, the values of average TTC for the different subject-vehicle speed ranges are very different, and this difference of average TTC for the different subject-vehicle speed ranges decreases as the relative speed range increases).

In addition, from Fig. 14 one could see that TTC tends to decrease as relative speed increases. For a certain relative speed range studied here, it seems that TTC increases as the subject-vehicle speed increases. However, from Fig. 15 one could see that time gap tends to increase as the relative speed range increases. For a certain relative speed range studied here, the time gap tends to decrease as the subject-vehicle speed increases. Furthermore, from Fig. 14 and Fig.15, one could see that TTC in the low speed range (v<50 km/h) is relatively steady compared with other speed ranges of the subject-vehicle, so is the time gap in the high speed range (90-110 km/h). Hence, it seems important to use both TTC and time gap in the car following behavior analysis for low speed range. While in the high speed ranges, time gap is more suitable to be the safety indicator in car-following situations.



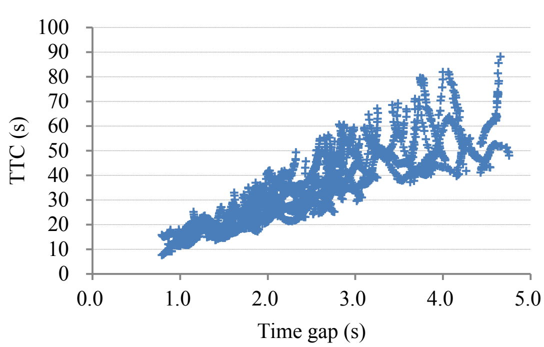


Fig. 13 The distribution of TTC and time gap when the relative speed range was 5-10 km/h with subject-vehicle speed range was 10-30 km/h (above) or 90-110 km/h (below)

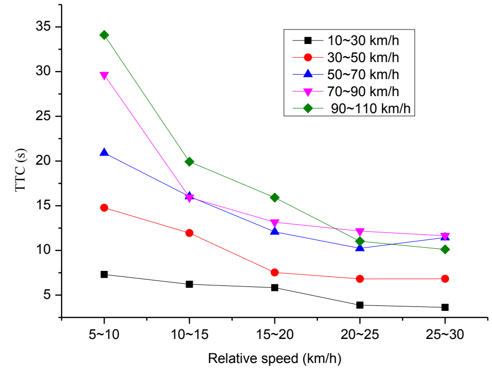


Fig. 14 Average TTC for different relative speed ranges and different subject-vehicle speed ranges

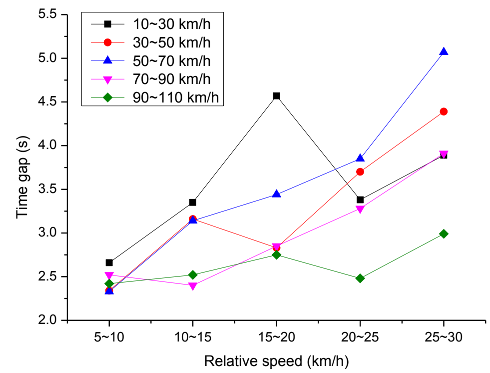


Fig. 15 Time gap for different relative speed ranges and different subject-vehicle speed ranges

IV. Discussion

Here, we compare our results with previous researches. In this test, the peak values of time gap frequency during car-following periods appeared at the range of 1.5 to 2.0 seconds, which is in line with the distribution observed in [8]. While the peak value of time gap to lead vehicle in [9] was found shorter than this study (1 to 1.5 seconds for speed range 30 to 69 km/h in Southampton, 1 to 1.5 seconds for speed range 30 to 49 km/h in Tsukuba, 0.5 to 1 seconds for speed range 50 to 69 km/h in Tsukuba). The difference may be explained by the traffic jam and lower speed on the urban road in their tests. Moreover, the distribution of gap distance is also similar with the results obtained by [10]. The peak value of gap distance frequency in [10] for all type of vehicles appeared at the range of 20 to 25 meters, which is similar to the range of 20 to 30 meters observed in this test.

In light of the results of this test and comparisons among literatures [7,9,10], we find that drivers drive mostly at the time gap less than 4 seconds or the gap distance less than 80 meters in the car-following situations. Perhaps, 4 seconds time gap or 80 meters gap distance could also be used as thresholds, in defining and identifying car-following events.

Even among only 12 drivers, the spread of gap distance was found bigger at high speed compared to that at low speed, similarly, the spread of gap distance was also found bigger on expressway than on national highway in this test. This is agreeing with what was found in [1,10,11]. However, the spread of time gap was similar in different speed limit conditions and on different road types. Fig.6 showed that the spread of average time gap is wide (can be anything from

1.5 to 6 seconds) for any average speed, although perhaps a lot are concentrating around 1.5 to 2 seconds. Nevertheless, the results in [7,14,15] showed that the tendency of time gap was decreasing as speed increased. This may be explained by congested road in [14], test conditions (using simulation in [15]), and no detailed values of speed ranges (only slow, medium and high instead in [7]), or other factors.

Besides the comparisons between time gap and gap distance, the relationship between TTC and time gap in different relative speed ranges and subject-vehicle speed ranges were also analyzed in this test. That is, for a certain relative speed range, TTC increases as the subject-vehicle speed increases. However, the time gap tends to decrease as the subject-vehicle speed increases. Furthermore, TTC in the low speed range (v<50 km/h) is found to be steady compared with other speed ranges. Similarly, the time gap in the high speed range (90-110 km/h) is also steady compared with other speed ranges of the subject-vehicle. Therefore, time gap is more appropriate for the analysis of car following behavior in the high speed ranges, but both TTC and time gap should be part of the safety indicator used in the low speed ranges. A driving simulator study in [16] also mentioned that driver could make a decision for accelerator release or brake activation in car-following situations in terms of the average value of time headway and TTC in the low speed ranges.

V. Conclusion

This paper mainly introduced car-following events definition and extraction rules from 64 objects based on radar data. Furthermore, it also described the distribution characteristics of time gap and gap distance for 12 professional Chinese drivers driving in real traffic, including comparisons among events, in different speed limits, and in different roads, together with the comparison of time gap and TTC in different relative speed ranges and subject-vehicle speed ranges. The results indicated that all of time gap, gap distance and TTC can be used as safety indicators of car-following situations. However, given that the indicator of time gap is less sensitive to the variations in speed and road condition compared with gap distance in this test, the indicator of time gap may be a much safer choice compared with gap distance for car-following behavior analysis. Furthermore, TTC in the low speed range (v<50 km/h) is found to be steady compared with other speed ranges of the subject-vehicle, so is the time gap in the high speed range (90-110 km/h). Therefore, time gap is more appropriate for the analysis of car following behavior in the high speed ranges, but both TTC and time gap should be part of the safety indicator used in the low speed ranges.

Limitations of this work include the followings. The data used here is only from 12 drivers. Though 12 drivers seem to be a small number, Higgs and Abbas [17] found that the results from 10 car-drivers in their study gave enough variation. The drivers were all driving school instructors; this may mean that the findings may only represent this specific driver population.

In the future, we want to compare if driver's speed control in car-following situations is affected by traffic culture (e.g., in different country), driver's experience, or size of the lead vehicle (e.g. car vs truck), etc. We want to study variability within individual driver's data using larger data set. Furthermore, we want to identify individual differences in car-following situations among drivers to improve development of advance driving assistant system.

Acknowledgment

T.L. and R.F. are grateful for funding support from Changjiang scholars and an innovative project team development plan (IRT17_95) and China Scholarship Council (201706560015). S. is grateful for funding support from Chalmers Area of Advance Transport. The work was done during T.L.'s research visit to Chalmers.

References

[1] Jiang, Jun, and J. Lu. "Car-following Behavior of Chinese Drivers." Transportation Research Board 94th Annual Meeting 2015.

[2] TRB, Highway Capacity Manual 2010. Washington, DC: Transportation Research Board, 2010.

[3] Pasanen, E., and H. Salmivaara. "Driving speeds and pedestrian safety in the City of Helsinki." Traffic Engineering and Control 34.6 (1993): 308-310.

[4] Vogel, Katja. "What characterizes a "free vehicle" in an urban area?." Transportation Research Part F: Traffic Psychology and Behaviour 5.1 (2002): 15-29.

[5] Pariota, L, et al. "Longitudinal control behaviour: Analysis and modelling based on experimental surveys in Italy and the UK." Accident Analysis and Prevention 89(2016):74-87.

[6] Lu, G., Cheng, B., Lin, Q., & Wang, Y. (2012). Quantitative indicator of homeostatic risk perception in car following. Safety science, 50(9), 1898-1905.

[7] Meixin Zhu, Xuesong Wang, and Xiaomeng Wang. "Car-Following Headways in Different Driving Situations: A Naturalistic Driving Study." CICTP 2016. 2016. 1419-1428.

[8] MENG Fan-xing, ZHANG Liang, ZHANG Wei. "A study on driver's time gap." Industrial Engineering and Management, 18.2 (2013): 131-135.

[9] Sato, Toshihisa, and Motoyuki Akamatsu. "Understanding driver car-following behavior using a fuzzy logic car-following model." Fuzzy Logic-Algorithms, Techniques and Implementations. InTech, 2012.

[10] Sanik, M. E., Prasetijo, J., Nor, A. H. M., Hamid, N. B., Yusof, I., & Jaya, R. P. "Analysis of car following headway along multilane highway." Jurnal Teknologi, vol. 78, no. 4, pp. 59 – 64, 2016.

[11] Sangster, John, Hesham Rakha, and Jianhe Du. "Application of naturalistic driving data to modeling of driver car-following behavior." Transportation Research Record: Journal of the Transportation Research Board 2390 (2013): 20-33.

[12] Siebert, Felix Wilhelm, et al. "The exact determination of subjective risk and comfort thresholds in car following." Transportation research part F: traffic psychology and behaviour 46 (2017): 1-13.

[13] Risto, Malte, and Marieke H. Martens. "Time and space: The difference between following time gap and gap distance instructions." Transportation research part F: traffic psychology and behaviour 17 (2013): 45-51.

[14] Brackstone, Mark, Ben Waterson, and Mike McDonald." Determinants of following headway in congested traffic." Transportation Research Part F: Traffic Psychology and Behaviour 12.2 (2009): 131-142.

[15] Lu, G., Cheng, B., Wang, Y., & Lin, Q. (2013). A car-following model based on quantified homeostatic risk perception. Mathematical Problems in Engineering, 2013.

[16] Mai, M., et al. Advancement of the car following model of Wiedemann on lower velocity ranges for urban traffic simulation. Transportation Research Part F (2017), article in press.

[17] B. Higgs and M. Abbas, "Segmentation and clustering of car-following behavior: Recognition of driving patterns," IEEE Trans. Intell. Transp. Syst., vol. 16, no. 1, pp. 81–90, Feb. 2015.