

Comparing time to collision and time headway as safety criteria

Güvenlik kriteri olarak çarpışmaya kadar geçen süre ve takip zaman aralığı karşılaştırılması

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Abstract

Examination of the criteria for maintaining distance between vehicles helps to better understand the behavior of following behavior and traffic flow. In this study, time headway (TH) and time to collision (TTC) criteria have been studied using driving simulator. TH is divided into two types, including braking TH, TH at the moment of considerable brake, and following TH, TH during following. The results showed that by reaching TTC to a threshold, braking TH has increased to 1.5 sec. and after this value, braking TH has remained constant. Also the comparison between braking and following TH showed that, unlike following TH, braking TH has less variance and its values did not differ significantly between lanes. That is, the driver is trying to observe a fixed amount of braking TH, 1.1 seconds, all the time, and not get closer to the front vehicle accordingly. It can be said that among the criteria, braking TH is the most important factor and considering it can be helpful in the car-following models.

Keywords: Time headway, Time to collision, Driving simulator.

Öz

Araçlar arasındaki mesafeyi korumak için kriterlerin incelenmesi yolun üzerindeki davranışları ve trafik akımını daha iyi anlamaya destek olur. Bu çalışmada zaman aralığı ve çarpışma süresi kriterleri sürüş simülatorü kullanılarak incelenmiştir. Zaman aralığı, frenleme zaman aralığı ve takip zaman aralığı'na ayrılır. Sonuçlar çarpışma zamanının (TTC) bir eşiğe ulaşmasıyla ve frenleme zaman aralığının (TH) 1.5 sn.'ye yükseldiğini ve bu değerden sonra sabit kaldığını gösterdi. Ayrıca, frenleme zaman aralığı ve takip zaman aralığı arasında karşılaştırma, zaman aralığı'nı takip etmekten farklı olarak, frenleme zaman aralığı'nin daha az varyansa sahip olduğunu ve değerlerinin seritler arasında önemli ölçüde farklılık göstermediğini gösterdi. Yani sürücü her zaman 1.1 sn. sabit bir frenleme zaman aralığı gözlemlemeye çalışıyor ve buna göre ön araca yaklaşıyor kriterler arasında zaman aralığı frenleme'nin en önemli faktör olduğu ve bunun dikkate alınması otomobil takip eden modellerde faydalı olabileceği söylenebilir.

Anahtar kelimeler: Takip zaman aralığı, Çarpışma zamanı, Sürüş simülatorü.

1 Introduction

In Iran, about 20,000 people die every year on urban and suburban roads, with a 20 percent share of accidents involving rear-end collisions [1]. These types of accidents often occur when a vehicle is moving behind another vehicle; hence two factors of time headway and time to collision are important. The time headway (TH) (Figure 1) is defined as the interval between the points passing through two consecutive vehicles (such as the front bumper) from an index point and calculated according to eq 1:

$$TH = t_i - t_{i-1} \quad (1)$$

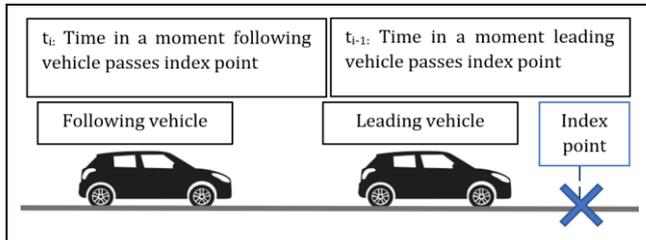


Figure 1. Time headway.

Various factors are involved in the occurrence of road collisions, of which human factors are considered the most

significant [2]. To better design behavioral countermeasures, it should be well understood the driving behavior which are involved in safety critical events [3]. One of this behaviors is the adopted distance during driving which can be expressed in TH or distance. TH is one of the important microscopic traffic flow parameters which is extensively applied in planning, analysis, design and operation of roadway systems [4]. TH has applications in capacity estimation, level of service (LOS) analysis, safety analysis, delay and gap acceptance studies, etc. of a roadway system [5],[6]. It is essential to accurately evaluate this parameter based on real behavior of drivers [7],[8]. There are many researches about the distribution and value of TH. Treiterer & Nemeth [9] found that nearly 50% of THs in interstate traffic were between 1 and 2 sec, and over 20% were below 1 sec. Von Buseck et al. [10] reported a median TH of approximately 1.4 sec in urban interstate traffic. Winkelbauer et al. [11] investigated the effect of the type of vehicle on TH. They found that the average of TH is between 1.4 and 1.7 sec when the leading vehicle is personal car. Yue et al. [12] by using city monitoring cameras data investigated the impact of the accident on drivers' TH. The results indicated ordinary TH (that is in the approximate period of 45 days had no accident) was averagely 2.56 sec (SD=0.3). Siebert and Wallis [13] also studied desired TH in 3 different site distance conditions on the field (clear, foggy, and truck) and in 3 different road types (in which speeds were 50, 100, 150 km/h). The results showed

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that in the clear weather condition, the minimum desired TH of most drivers were 1.75, 1.5 and 1.25 sec for speeds of 50, 100 and 150 km/h, respectively. Khansari et al. [14] considered TH as safety factor to divide following behavior into free driving, lane-based following and non-lane-based following. They suggested thresholds for swithing between them.

Another important parameter in the context of rear-end collisions is time to collision (TTC), which has been applied beneficially as a safety indicator in safety analysis. The TTC concept was introduced in 1971 by the US researcher Hayward [15]. TTC value at an instant t is defined as the time that remains until a collision between two successive vehicles would occur if the speed difference maintained [16]. The formula of TTC is presented in eq 2:

$$TTC_i = \frac{X_{i-1}(t) - X_i(t) - l_i}{\dot{X}_i(t) - \dot{X}_{i-1}(t)} \quad \forall \dot{X}_i(t) > \dot{X}_{i-1}(t) \quad (2)$$

Where \dot{X}_i , X_i and l_i are the speed(m/s), location and length(m) of the following vehicle, respectively, and the $i - 1$ index of the leading vehicle. Given the importance of TTC in the safety approach, a threshold should be chosen to distinguish safe and critical conditions [17]. Hirst and Graham [18] reported that a TTC measure of 4 sec could be used to discriminate between cases where drivers unintentionally find themselves in a dangerous situation from cases where driving remains in control. Saffarzadeh et al. [1] also mentioned that as drivers' behavior is not constant in different situations. There is no definite value for TTC threshold to enable discrimination between safe and unsafe car-following situations. So, a wide range of values from 0.5 to 10 sec are selected as TTC threshold.

Both TH and TTC are safety indices associated with rear-end collision and are mathematically related. Therefore, it is possible that these two parameters are in fact significantly correlated and that a new safety index can be reached based on them. To study this relationship, Van Winsum & Heino [19] observed the behavior of drivers in the driving simulator in two different groups. In the first group, the speed of the leading vehicle was reduced from 60 to 40 km/h and in the second group the speed decreased from 50 to 30 km/h. TH and TTC were collected and plotted as the drivers began to brake. For the first group, the TTC at the beginning of braking was between 3 to 6 and the TH was 1.5 to 2.5 sec, and for the second group, the TTC was between 3 to 6 and the TH was 1 to 1.5 sec.

Vogel [20] collected data from an intersection. He found that there was a correlation between TH and TTC. This is expected because vehicles with larger THs tend to have larger TTCs. However, this correlation disappeared when the TH was lower than 6 sec.

A few researches have been done on the relationship between TH and TTC, so this study investigates more closely the relationship between them. These indicators need to be identified separately in each lane because in spite of the hypothesis that the following behavior of drivers on the same lanes is the equivalent, it seems necessary to examine whether it is true [21]. Ayres et al. [22] reported the speed and TH of drivers in three different conditions (including free flow, heavy traffic, and peak hours) and in different lanes from one of the US highways. They found peak hour eliminates inter-lane variations of TH, but drivers in the fast lanes generally choose shorter THs than slower-lane drivers when traffic conditions permit higher speeds (except for lane 1 in free flow condition). They also found that 1-2 sec THs are typical in all lanes under

high volume traffic conditions, but some drivers will choose the lower speeds and longer headways in the slower lanes outside of peak hour. Abtahi et al. [23] recorded an interurban highway traffic flow. They found that the behavior of drivers on different lanes is different, even if the volume of traffic is the same.

To investigate the TH accurately, TTC, and their relationship, here a research based on a driving simulator is designed. Driving simulators have many advantages over real driving test. Scenarios that contain traffic conflicts can be created as required, and experiment can be conducted without a threat to the life and health of participants [24]. One of the advantages of using a driving simulator in this study is that the data are continuously recorded and can be separated into different lanes. In addition, almost any kind of road environment can be presented with this tool, while data acquisition is usually complete and straightforward [25].

This study in two aspects, by using inferential statistics, can be an addition to previous researches on the difference between TH and TTC as safety criteria. First, instead of addressing a speed range, all speed ranges were considered. Second, by categorizing the data based on the lane and driving condition, it has been tried to study TH deeper.

Section 2 illustrates the data collection method. Section 3 investigates the relation between TTC and braking TH. Section 4 deals with the difference between braking TH and following TH and examining them in different lanes. Section 5 will be the conclusion of this study.

2 Data collection

The following research was carried out by the simulator of Amir Kabir University of Technology (Figure 2).



Figure 2. AUT driving simulator.

It was performed by 118 people in the simulator including 86 men (average age=29.8, SD=10.6) and 32 women (average age=24.4, SD=3.87). Each of the drivers had about 5 min. to warm up and then started driving on an 8-lane arterial road (4 lanes in each direction). The numbering of the lanes (Figure 3) is that lane 1 is the closest lane to the median and lane 4 is the most right lane (closest to the shoulder). Iran is a right-hand-driving country, that is the vehicles on left lanes are usually faster than those of right lanes. Khansari et al. [21] showed that drivers on faster lanes are more aggressive. Weather conditions are simulated on a sunny day and conditions such as rain and fog that affect the behavior of drivers are not taken into account.

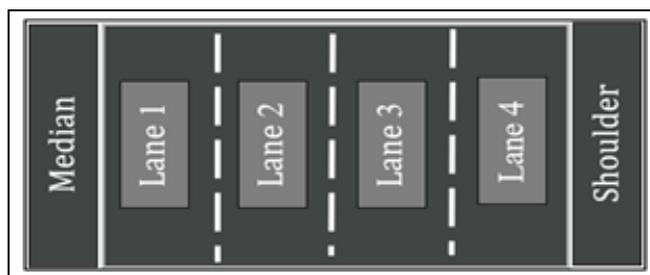


Figure 3. Lane numbers.

In this study, the data have a broad range of speeds to consider more comprehensive study. This research has no limitation such as Van Winsum & Heino's paper [19] which was conducted only at predefined speeds. Figure 4 shows the distribution of drivers' speeds by gender.

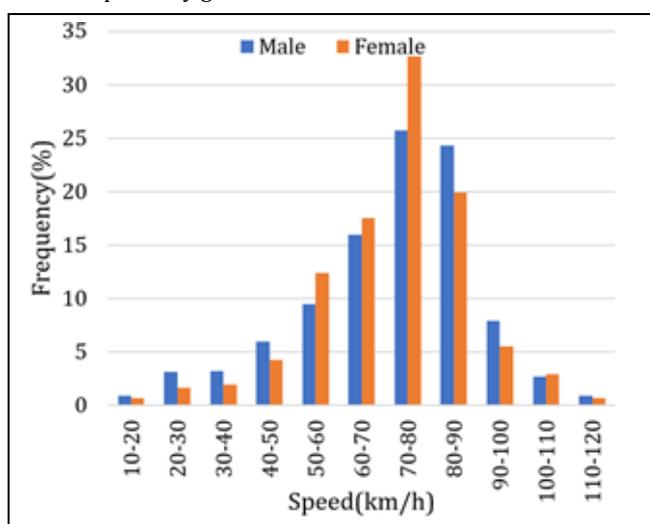


Figure 4. Distribution of drivers' speed.

3 Relationship between TTC and braking TH

TH and TTC are both important safety indicators especially in rear-end collisions. Therefore, understanding the relationship between these two important factors would be necessary. To maintain the safety, drivers do not approach the leading vehicle closer than a certain distance and start braking if they get too close.

This results in an increase in the TH and usually leads to negative TTC, as the speed of following can be slower than the leading. Here, the TH at this moment (the beginning of braking and decelerating) is specified as the risk threshold for drivers and is called as the braking TH. The following conditions are assumed to obtain this threshold from the trajectory data:

- Speed of following vehicle was larger than 50 km/h,
- Relative speed (speed difference between leading and following vehicle) was larger than 10 km/h,
- The sign of TTC turned negative (due to the changing of relative speed of two consecutive vehicles).

To better understand the concept of braking TH, Figure 5 shows the diagram of following of a driver over 35 sec. The blue line represents the difference between the speed of the following vehicle and the leading vehicle, the gray line indicates the speed of the following vehicle and the orange line indicates the distance headway of the two vehicles. The distance headway is

defined as the distance from a selected point on the lead vehicle to the same point on the following vehicle. Usually, the front edges or bumpers are selected [26]. The vertical dotted line represents the moment of braking or deceleration, and the TH at these points is defined as the braking TH. Negative relative speed at these points means that the following chooses a lower speed to avoid collision with the leading vehicle.

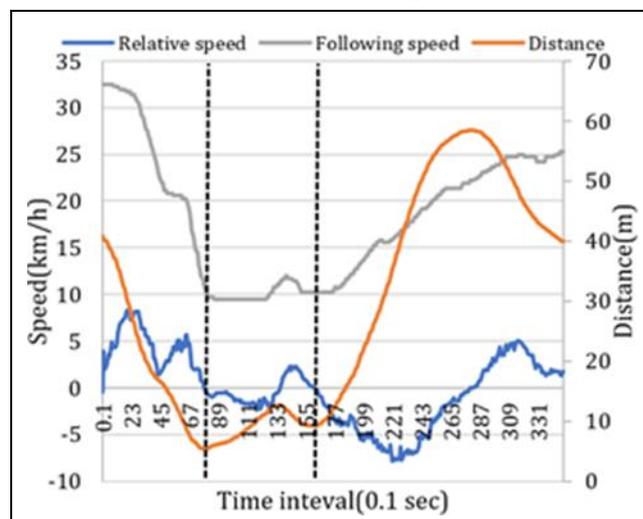


Figure 5. Recording braking TH based on relative speed and distance headway.

As TTC was used to estimate braking TH, their correlations would be discussable. As expected, with the increase in TTC at the moment of braking, the braking TH has increased somewhat and their correlation has decreased in higher TTCs. Figure 6 shows the relationship between braking TH and TTC. The TTCs are limited to 20 sec which is as it is assumed that in higher TTCs, the behavior of the following vehicle is not related to the behavior of the leading vehicle.

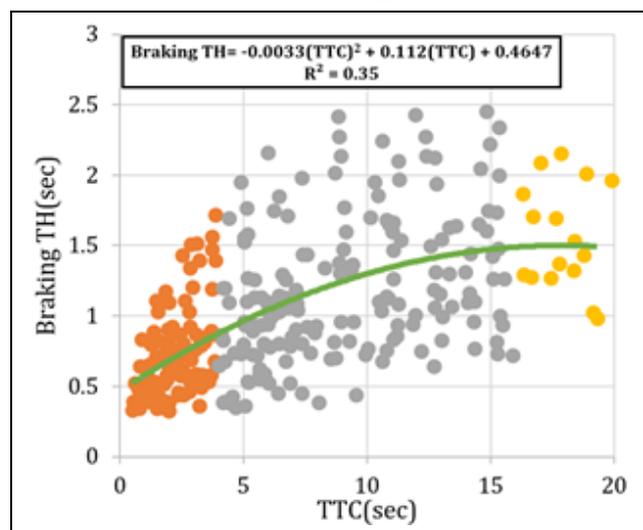


Figure 6. Braking TH and TTC

For better understanding that 20 sec takes into account the entire significant range of TTCs, consider 90 and 70 km/h for the following and leading vehicle, respectively, and the length of 4 m for the leading, then the distance headway between two vehicles will be about 115 m which is so large.

The second-order regression provides a fairly adequate fit for the above data. It should be noted that, considering that the data is aggregate and about the behavior of human, $R-sqr=0.35$ can be acceptable [27]. It can be assumed that the above graph can be divided into three parts based on the correlation coefficient value. By intuitive judgment 4 and 16 sec points were selected as TTC thresholds for segmentation approximately. Table 1 compares the correlation coefficients in these intervals. According to the correlation coefficient values, the relationship between TTC and braking TH can be divided into three intervals: high, low and negligible.

Table 1. Correlation between braking TH and TTC.

Correlation coefficient	Range of TTC(sec)	Segment
0.62	0-4	High
0.31	4-16	Low
-0.06	16-20	Negligible

This trend of change indicates that as TTC increases, its relationship to braking TH is reduced and drivers pay less attention to TTC. It may be interpreted that braking TH would be the main criterion for risk perception. The box plot (Figure 7) and ANOVA test (Table 2) are presented below to better illustrate the differences between the braking TH in the 3 different groups. The results showed that in TTCs larger than 16 sec there is hardly relationship between TTC and braking TH and the braking TH value remains almost constant. There is also a large difference between the correlations of higher and lower 4 sec of TTC and it can support the choice of a 4 sec as a threshold point.

Table 2. ANOVA result of braking TH for different TTCs.

Braking TH(sec)	0-4	4-16	16-20
Average	0.7	1.2	1.6
Variance	0.1	0.26	0.14
Confidence Interval	95%		
F	46.34		
P-value	0.000		
F critical	3.03		

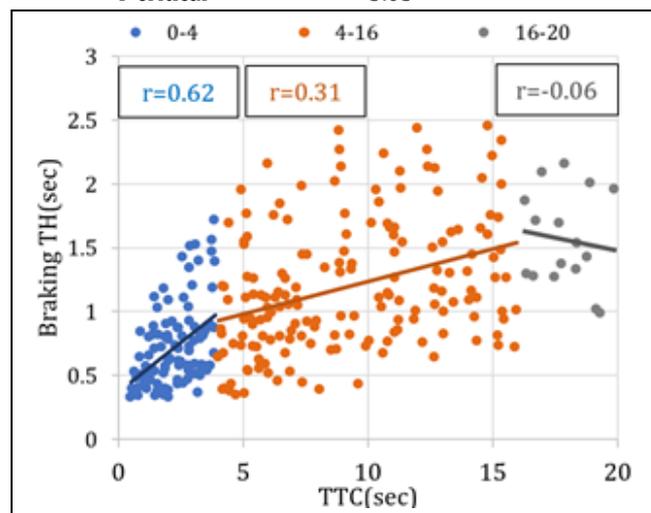


Figure 7. Correlation and trend line of braking TH for different TTCs.

Table 2 compares the different braking TH values in the intervals. It indicates that the set of braking TH of each interval has a significant difference and that the thresholds selected can be appropriate. The results show that TH plays a much more important role than TTC, because by increasing TTC, the

braking TH has increased. But when braking TH has reached the of 1.5 sec, it is almost fixed and the driver observes this value and does not consider the TTC, that is to say braking TH would be the control criteria for the drivers. Therefore, in the next section TH will be examined the in more detail. Figure 8 depicts the correlation and trend line for each segment.

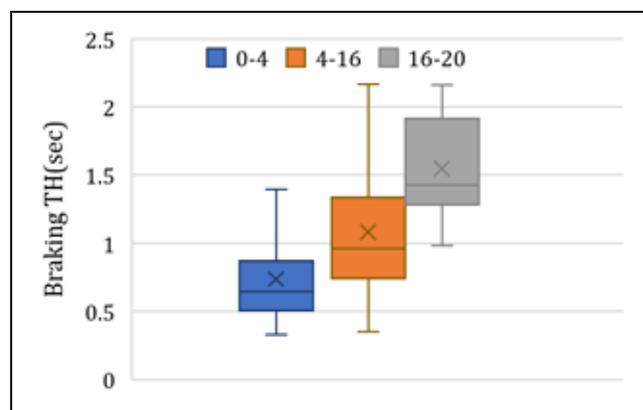


Figure 8. Boxplots of braking TH for different TTCs.

4 Braking and following TH

The concept of car-following is widely used to identify the driver's behavior and is used to investigate the TH more precisely. The basic assumption in the concept of car-following is that each driver tries to maintain the desired following distance through throttle and braking [28]. The TH is considered as the following TH when the vehicle moves at an almost constant speed equal to the front vehicle and behind it. This section examines the differences between braking and following TH. The data of both types of TH were taken separately for each lane to show their variations. Its related box plots are shown in Figure 9.

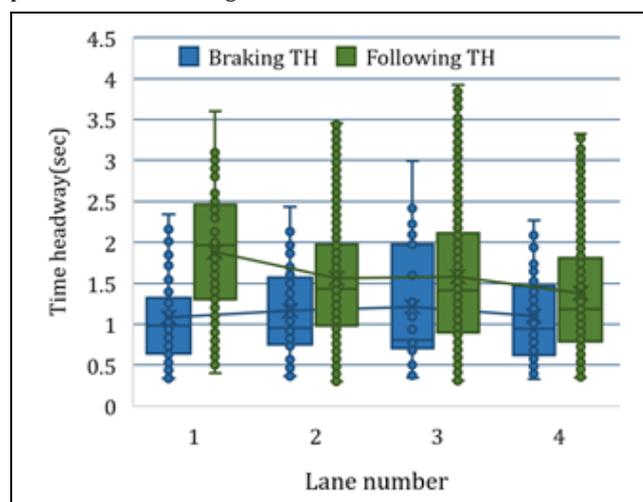


Figure 9. Comparison between braking and following TH in different lanes.

Also, the T-test (Table 3) showed a significant difference between the braking and following headway. The lower braking TH is due to its nature because it represents the least safety while the following TH is desired for driving. In other words, the braking TH occurs only in one moment, and its selection as following TH increases the potential of accident. Generally, it can be said that the drivers first approach front vehicle and then

put some distance. This behavior is also mentioned in the Wiedemann model where drivers adjust their behavior over a range of distance, and here the lower limit can be defined braking TH. Following mode in Wiedemann model states the driver follows the leading vehicle without any conscious acceleration or deceleration. Driver keeps the safety distance more or less constant, but again due to imperfect throttle control and imperfect estimation of the speed difference oscillates around zero [29].

Table 3. T-test between braking and following TH.

Time headway(sec)	Braking TH	Following TH
Mean	1.1	1.5
Variance	0.39	0.60
SD	0.62	0.77
confidence interval	95%	
t Stat	-12.8	
P(T<=t) one-tail	0.0	
t Critical one-tail	1.65	
P(T<=t) two-tail	0.000	
t Critical two-tail	1.97	

Also, Figure 9 shows the TH smaller than recommended safe value, 2 sec. Ayres et al. [16] showed that most people's behavior is not to maximize safety and minimize risk, but to improve their performance. Abtahi et al. [17] also observed that, in the car-following mode, many drivers apply TH smaller than safe TH. Saha et al. [30] by comparison of statistical parameters demonstrated that at all flow rates the distributions were positive-skewed which indicates increment in unsafe situations. Highway observations showed that many drivers adopt the TH below 1 sec [31],[32]. Khansari et al. [21] showed that dangerous and close following had a significant portion of the TH field data. Since TH is a very important criterion in safety and design considerations, it has been examined for each lane.

Figure 10 and Figure 11 show the histogram of braking and following TH for each lane. ANOVA test was used between lanes for braking and following TH. Unlike braking TH (Table 4), no significant difference was observed between lanes for following TH (Table 5).

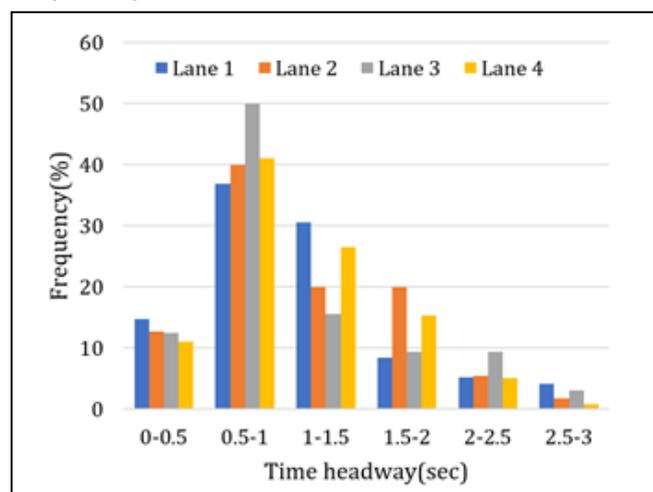


Figure 10. Distribution of braking TH for different lanes.

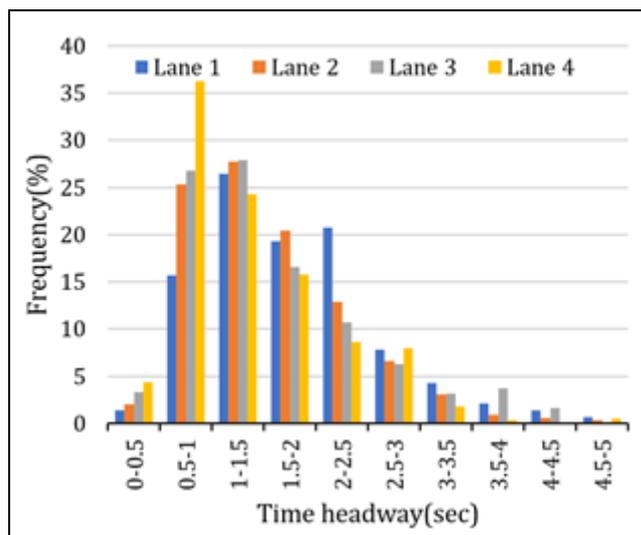


Figure 11. Distribution of following TH for each lane

Table 4. ANOVA test of braking TH between different lanes.

Braking TH(sec)	Lane 1	Lane 2	Lane 3	Lane 4
Average	1.1	1.2	1.2	1.1
Variance	0.35	0.42	0.54	0.34
SD	0.59	0.65	0.73	0.58
Confidence Interval	95%			
F	0.47			
P-value	0.7			
F critical	2.64			

Table 5. ANOVA test of following TH between different lanes.

Following TH(sec)	Lane 1	Lane 2	Lane 3	Lane 4
Average	1.9	1.6	1.6	1.4
Variance	0.60	0.57	0.78	0.55
SD	0.77	0.75	0.88	0.74
Confidence Interval	95%			
F	83.93			
P-value	0.000			
F critical	2.61			

As the result, unlike following TH, the braking TH wouldn't be lane-dependent and its variance is less. The following TH would vary from one lane to another, and with the increase in lane speed, it would increase.

The nonequivalent distribution of drivers' gender between lanes may affect the validity of above results for following and braking TH. In other words, if a gender is dominant in a lane, then the results obtained from that lane are affected by the behavior of that gender. To address this, Figure 12 shows that the distribution of male and female drivers between the lanes are almost the same, and the gender factor has no effect on the analysis. of course, like field data, the number of men in the simulator was greater.

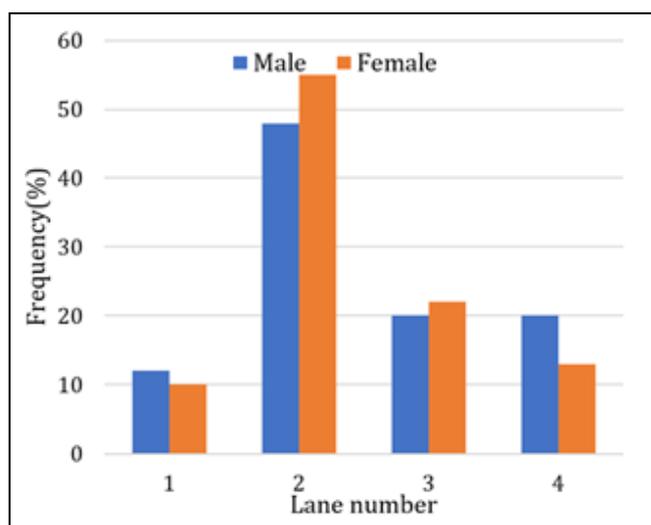


Figure 12. Distribution of driving duration in each lane for men and women.

5 Conclusion

118 people were recruited to drive on a highway in the simulator in order to evaluate two safety criteria: TH (braking and following) and TTC. In previous studies, these criteria had been examined separately, while here they have been studied together. First, the relationship between TTC and braking TH was investigated, then then breaking TH was compared with following TH.

The drivers brake to prevent accident with their front car, the question is, what criteria do drivers consider to be in safe situation? By investigating the changes and correlations of braking TH and TTC, 4 and 16 sec were estimated as thresholds for determining the high, low and negligible segments. The diagrams showed that the braking TH is the main criterion for safety because by increasing TTC to upper than 16 sec, braking TH remains constant. In other words, drivers use braking TH as a measure of risk perception. The braking TH is defined as the TH of the moment, in which the sign of TTC turned negative due to tangible braking. It is worth noting that there are other TH where the driver brakes but they are ignored. Because the goal was to find an occasion that the driver felt completely in danger and did not get closer to his front vehicle. By switching the TTC from positive to negative, it ensures that the following is moving away from leading vehicle.

In following situation, when the speed of two consecutive vehicles is almost equal, the driver considers the minimum safe distance, which is called following TH. By comparing the braking and following TH, respectively 1.1 and 1.5 sec, it was observed that drivers have chosen larger following TH, about 0.4 sec. This may be due to the longer time span of driving with following TH. Drivers can endure a short duration for close TH, but maintaining it for longer duration would be unacceptable. The results showed a significant difference between the braking and following TH. The variance of braking TH was less than following TH. Braking TH wasn't lane dependent, in contrast to following TH, which has increased by increasing lane speed.

It would say that there more homogeneity and consistency among drivers for braking TH and it can be considered as primary safety factor for drivers. In summary, the most effective factor for safety would be the braking TH, which is

followed by following TH and TTC, and it is better to be considered in car-following models and in driving behavior studies.

6 Author contribution statements

In the scope of this study, the Ehsan RAMEZANI KHANSARI and Sina MOOGHEHI conceived of the presented idea, carried out the experiments, analyzed data, and wrote the manuscript and Fereidoon MOGHADAS NEJAD, supervised the project.

7 Ethics committee approval and conflict of interest statement

Verbal informed consent was obtained from all subjects before the study. There is no conflict of interest with any person/institution in the article prepared.

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