Direct Evidence of the Inverse of TTC Hypothesis for Driver’s Perception in Car-Closing Situations

Takayuki Kondoh 1) Nobuhiro Furuyama 2) Toshiya Hirose 3) Toichi Sawada 4)

1) Tokyo Institute of Technology, Interdisciplinary Graduate School of Science & Engineering
4259 Nagatsuta, Midori, Yokohama, Kanagawa, 226-8502, Japan (E-mail: kondoh.t.aa@m.titech.ac.jp)
2) Waseda University
2-57-15 Mikajima, Tokorozawa, Saitama, 359-1192, Japan
3), 4) Shibaura Institute of Technology
3-7-5 Toyosu Koto Tokyo, 135-8548, Japan

Received on January 9, 2014
Presented at the First International Symposium on FAST-Zero’11 on September 6, 2011

ABSTRACT: This paper describes the experiments involving a driving simulator that examined the implicit relationship between subjective perception and objective closeness of the gap between the host car and the lead car, the latter closing to the former at a constant relative velocity / at a constant relative deceleration rate. The subjective perception of closeness was quantified in terms of 1/TTC (\(\Theta\), where \(\Theta\) is the driver’s visual angle of the lead car). The results suggest that the drivers perceive the lead car closing in terms of 1/TTC both in the constant relative velocity condition and the constant deceleration condition.

KEY WORDS: human engineering, risk recognition, cognitive, perception, TTC, car-closing situations [C2]

1. Introduction

The ratio of rear-end collisions to all automobile accidents expresses a percentage of approximately 32\% (1). Therefore, it is crucial to take measures against these types of collisions in order to decrease the number of car accidents on the whole and/or minimize the damage caused by these types of accidents. Various technologies have been developed and implemented in new products to achieve this goal, including the Forward Collision Avoidance Assist Concept (2) and Forward Vehicle Collision Mitigation Systems (3). The acceptability of these systems would be low, however, if they were suddenly activated when the drivers were not expecting them to be. On the other hand, the drivers’ over-trust in these systems is also problematic, because the drivers’ motivation, level of arousal, situational awareness, and so forth needed for safe driving can suffer. Research on risk evaluation indices in car-following situations has been conducted, of which one of the most important indices is the 1/TTC (Time-to-Collision or \(\tau\)) (4–7) by taking these problems into account as the design principles. And the driver assistant system using the risk evaluation index was proposed, moreover the risk index was used as the control parameter of the force feedback pedal for the driver (8). It has been argued that TTC can be approximated by using, for example, the visual angle of an object (e.g., the lead car) divided by the rate of the change in visual angle when the lead car closes. There have also been many studies (9)–(12) explaining the behaviors of humans and animals as they get closer to objects in a given environment in terms of the TTC.

Studies (4) on 1/TTC suggest that the larger the value of 1/TTC, the greater the driver’s risk feelings when the lead car is closing. However, no study has demonstrated the linear relationship between the two variables. The present study attempts to directly examine the nature of the perception in such cases, instead of indirectly scrutinizing the validity by observing the other behaviors, such as braking behavior.

In particular, we try to systematically look into the entire process, starting from the stimulus presentation to the given perception in terms of the 1/TTC, by conducting experiments using a driving simulator. Experiment 1 examines the timing of the perception at the onset of the lead car closing in terms of the 1/TTC. Experiment 2 quantifies the driver’s subjective evaluation of the rate of closing on the lead car, using a magnitude estimation method (13).

2. Subjective Closing Indices in Car-following Situations
2.1. Inverse of TTC and its characteristic

Experiment 1 examines the timing of the perception at the onset of the lead car closing in terms of the 1/TTC. Experiment 2 quantifies the driver’s subjective evaluation of the rate of closing on the lead car, using a magnitude estimation method (13).

To understand the driver’s perception of the lead car closing, it is important to elucidate what counts as an index of perception of closing. In ecological psychology, James J. Gibson refers to this index as “ecological physics” (14). When the lead car closes the host car, the degree of closeness is usually expressed in terms
of the distance headway or relative velocity between the two vehicles, but these indices are hardly ones that humans can perceive directly. What is available to the driver for perceiving the lead car closing is, instead, change in visual angle. The present study considers it as a valid example of what Gibson called “ecological physics.” 1/TTC can be defined in terms of the rate of change in visual angle of the lead car (θ) divided by the θ itself, and it is equal to the relative velocity divided by the distance headway:

$$\frac{1}{\text{TTC}} = \frac{1}{\tau} = \frac{\dot{\theta}}{\theta} = \frac{V_r}{D}$$ (1)

where $D$ is the distance headway between the lead and host cars, and $V_r$ is the relative velocity between the two vehicles, and $\theta$ is the driver’s visual angle of the lead car. By definition, the 1/TTC asymptotically increases as the distance headway shortens and/or the relative velocity increases. Fig.1(a) shows a profile of the 1/TTC as the lead and host cars close at a constant relative velocity (5.6, 11.1, 16.7, 22.2, and 27.8 m/s), where the initial distance headway was 60 m, given that the initial velocity of the two vehicles is 27.8 m/s (the x’s in the figure show the plots at 0.1-sec intervals). Fig.1(b) shows a profile of the 1/TTC as the lead and host cars close at a constant deceleration (1, 2, 3, 4, 5, 6, 7, 8, and 9 m/s²), where the initial distance headway was 60 m, given that the initial velocity of the host and lead cars were both 27.8 m/s (the x’s in the figure show the plots at 0.1 sec intervals). The impact of the 0.1-sec intervals on the 1/TTC is larger depending on the value of the relative velocity (or deceleration of the lead car). Figs.2(a) and (b) show the 1/TTC profiles as the lead and host cars close at a constant relative velocity and at a constant deceleration, respectively, where the initial distance headway is 20, 30, 40, and 60 m, given that the initial velocity of the host and lead cars were both 27.8 m/s. The impact of the 0.1-sec intervals on the 1/TTC is larger as the initial distance headway decreases.

2.2. Inverse of TTC when the two vehicles close at an inconstant relative velocity

TTC is by definition a time-to-collision with an assumption that the relative velocity between the two vehicles is constant. However, in reality, the relative velocity is seldom constant, thus this has led a controversy as to the validity of TTC. David Lee argued(10) that TTC is directly specified by the visual angle of an object (θ) for the visual system of the host car’s driver, divided by the angular velocity of the visual angle (\(\dot{\theta}\)), given that the relative velocity of the two vehicles is constant (David Lee employs the term τ to mean what is referred to as TTC in the automobile engineering). When the relative velocity is not constant, the aforementioned relationship holds as an approximation, because the drivers can update their TTC estimates based on the changing visual angle as they close on the lead car(15).

The authors echo David Lee’s seminal work(10) on driving behavior, in considering that driving behavior is one example in which the general principle of τ theory (Lee’s theory) holds true. In fact, we have argued that it is possible to evaluate the correlation between the feelings of risk(14). Although there are...
3. Experiment 1: Perception of the onset of Lead Car Closing

This chapter reports on an experiment that further examined the driver’s perception of the onset of the lead car deceleration. We found that the perception was constant in terms of the 1/TTC, regardless of the initial distance headway, if the participants’ response time is taken into consideration.

3.1. Methodology

3.1.1. Apparatus

A motion-based driving simulator (DS) (Fig. 3) capable of controlling the experimental conditions was used in the present experiment. This driving simulator has a wide-angle field of view consisting of three screens that are 0.79 rad (45 deg.) horizontally x 0.52 rad (30 deg.) vertically and that have a high resolution of 2.9 x 10^-4 rad/pixel (1.0 arcmin/pixel). As mentioned earlier, the visual information from the screens constitutes the bulk of the information captured by the driver while driving.

3.1.2. Participants

Eight participants took part in this experiment. All of them had driver’s licenses; they had normal, or corrected to normal, vision, and their average age was 26 years old (SD = 11.0, ranges between 22 and 54 years old). They usually drove at least three times a week. They provided a written informed consent after receiving an explanation about the experiment.

3.1.3. Procedure

The participants drove in these car-following situations, using a driving simulator at fixed speeds of 27.8 m/s (100 km/h) and with constant distance headways of 20, 30, 40, or 60 m to the lead car. The lead car’s initial speed was 27.8 m/s (100 km/h), and its deceleration rate was constant in a range of between 1 ~ 9 m/s^2. The participants were instructed to place their right foot on the brake pedal and press it as soon as they perceived the lead car closing. This way, the temporal structure of the perception and the onset of pressing the brake could be correctly measured. The participants practiced driving the DS to become used to it prior to the experiments. They were not allowed to control the gas pedal, and the velocity of the host car was controlled by the host computer until the driver pressed the brake pedal.

3.1.4. Data Analysis

Since we were concerned with identifying the exact timing of the perception of the onset of the lead car deceleration, while minimizing the variances that may arise from the 1/TTC characteristics, the estimates of when the driver decided to press the brake pedal was calculated in the following way: i) we measured the time the brake was pressed; ii) the average reaction time of each participant obtained in a separate experiment was subtracted from the outcome of i) (i.e., the time at which the actual perception occurred) (See Appendix I for how the average reaction time of each participant was obtained); and iii) the 1/TTC was estimated using the outcome of ii) because the TTC value is given for a certain time because we experimentally controlled the relative velocity at any given moment. For example, in case where the average reaction time obtained for a participant by an independent experiment is 0.4 second, and the brake reaction time obtained for the same participant in the experiment under examination is 50.6 second in elapsed time of the experiment, the timing of the perception of the onset of the lead car deceleration is 50.2 second (=50.6-0.4). Based on this as an estimation of exactly when the participant perceived the lead car start decelerating, 1/TTC at the time of perception is further estimated using relative velocity and distance headway at the time (50.2 second passed since the onset of the experiment).

3.2. Results

Fig.4 shows the 1/TTC average for each participant when they pressed the brake pedal as soon as they started closing on the lead car as a function of the initial distance headway. The data in this figure includes the participants’ response time. As evident in the figure, the shorter the initial distance headway, the greater the 1/TTC value.

Fig.5 shows the average 1/TTC for each participant when they are estimated to have decided to press the brake pedal as soon as they started closing on the lead car as a function of the initial distance headway (the estimation is the same data as in Fig. 4, but with the response time of each participant as shown in Table 6 in Appendix II taken into account). The figure shows that the drivers appeared to constantly decide when to press the brake pedal in terms of the 1/TTC.

Fig.6 shows the 1/TTC average for all the participants when they perceived to be closing on the lead car using the initial distance headway. The 1/TTC is constant regardless of the initial distance headway in the entire tested range. The repeated-measures one-way ANOVA conducted on the data did not
indicate any statistically significant effect of initial distance headway.

4. Experiment 2: Quantification of Perception of Lead car Closing

The present experiment examined the theoretically deduced assumption that the 1/TTC can be approximated by \( \dot{\theta}/\theta \) (Formula (2)), by delineating the relationship between the driver’s subjective evaluation of the lead car closing and the actual stimuli. To achieve this, the intensity of the stimuli is defined as the target stimulus divided by the standard stimulus in terms of the relative velocity or deceleration, or as \( \dot{\theta}/\theta \), which is taken as an approximation of the 1/TTC in the application of the magnitude estimation method\(^{(12)}\).

4.1. Methodology

4.1.1. Apparatus

We used a simple driving simulator (SDS, Fig. 7) consisting of a display, a steering wheel, a gas-pedal, and a brake-pedal. The size of the display (EIZO, FlexScan T966) was 0.20 rad (11.4 deg.) horizontally x 0.15 rad (8.5 deg.) vertically, with a high resolution of 1.2 x 10^{-4} rad/pixel (0.4 arcmin/pixel).

What the participants saw in the SDS was a 1.70 m wide lead car on a straight highway background. The display was surrounded by a curtain so that the participants could not see anything other than the display. The SDS allows us to control the distance headway, relative velocity, and deceleration of the lead car. The height of the eye-point and the center of the display were both set at 1.20 m because the motion picture shown on the display was assumed to be captured at a height of 1.20 m, which reflects a real driving situation.

The size of the displayed lead car was determined by ensuring that its visual angle was the same as that from a real driving situation. The distance between the display and the participant was one meter.

4.1.2. Participants

Nine male participants took part in this experiment. All the participants had normal (or corrected to normal) vision. The average age was 22.7 years old (SD= 0.87, the range was between 22 and 25 years old). They signed a written informed consent form after receiving an explanation about the experiment.

4.1.3. Procedure

The goal of this experiment (Exp. 2) was to elucidate the relationship (1) between the driver's subjective evaluation of the
relative velocity and the actual relative velocity of the host car with respect to the lead car (hereafter referred to as the "constant relative velocity condition"), and (2) between the driver's subjective evaluation of the lead car's deceleration and its actual deceleration (hereafter referred to as the "deceleration condition").

The subjective evaluations of the relative velocity between the host and lead cars, and the lead car's deceleration (in short, closeness) were quantified by using the magnitude estimation method. Tables 2 and 3 list the detailed experimental settings under the constant relative velocity condition and deceleration condition, respectively.

The lead car’s decelerations, relative velocities, and initial distance headways were set to 1-9 m/s², 5.6-27.8 m/s, and 40-200 m, respectively. The initial velocity of the host car was set to a constant 27.8 m/s (100 km/h). The participants were instructed to drive an approximately straight road on an expressway, put their right foot on the gas pedal as if they were controlling the car’s velocity. The participants saw the lead car running at 27.8 m/s and starting to close. The participants' task was to compare the target and standard stimuli, the latter being 16.7 m/s under the constant velocity condition and deceleration condition, respectively.

| Parameters | Conditions |
|------------|------------|
| Initial Following Velocity (m/s) | 27.8 |
| Initial Distance Headway (m) | 40, 80, 120, 160, 200 |
| Relative Velocity (m/s) | 5.6, 11.1, 16.7*, 22.2, 27.8 |

* shows as standard stimulus on this experiment

Table 3 Experimental Conditions of Lead Car’s Deceleration

| Parameters | Conditions |
|------------|------------|
| Initial Following Velocity (m/s) | 27.8 |
| Initial Distance Headway (m) | 40, 80, 120, 160, 200 |
| Deceleration of Lead Car (m/s²) | 1, 3, 5*, 7, 9 |

* shows as standard stimulus on this experiment

We adopted two different approaches to define the intensity of a stimulus. The first approach defines the intensity of a stimulus as the target stimulus divided by the standard stimulus in terms of relative velocity or deceleration. For example, the intensity of a stimulus from a target stimulus of 11.1 m/s against the standard stimulus of 5 m/s² is 1.8. The second approach defines the intensity of a stimulus in terms of visual angle. The objective intensity of the stimulus in terms of visual angle is computed by formula (5) or (10) in Appendix II. For example, the intensity of a stimulus from a target stimulus of 11.1 m/s against the standard stimulus of 5 m/s² is 0.67. Furthermore, a target stimulus of 9 m/s² against the standard stimulus of 5 m/s² is 1.8. The second approach defines the intensity of a stimulus in terms of visual angle.
m/s against the standard stimulus of 16.7 m/s is 0.67 (see also, formula (5) in Appendix II). Furthermore, a target stimulus of 9 m/s against the standard stimulus of 5 m/s is 1.3 (see also, formula (10) in Appendix II).

4.2. Results

Fig. 8(a) shows the relationship between the intensity of the stimulus (as the target stimulus divided by the standard stimulus) and the driver’s subjective estimates of the closeness of the lead car with respect to the standard stimulus, regardless of the initial distance headway. The data shown are for the constant relative velocity (circle in blue) and the deceleration conditions (x in red). The approximation curve for the constant relative velocity condition is shown as the blue line, and that for the deceleration condition as the red line. This approximation curve was calculated by the least-squares method for the data of the intensity of the stimulus and subjective estimates. Note that the power exponent under the deceleration condition is far below 1, while that under the constant relative velocity condition is nearly 1.

Table 4 lists the power exponents of the approximation curves for the constant relative velocity conditions for different initial distance headways, and the power exponents in the 0.93-1.03 range, and their correlate coefficients in the 0.91-0.97 range. The table also lists the power exponents of the approximation curves for the deceleration condition at different initial distance headways, the power exponents in the 0.53-0.61 range, and their correlate coefficients in the 0.94-0.96 range. The differences in these results, if any, were very small among the different initial distance headway conditions.

Table 5 is the same as Table 4, except that the actual intensity stimulus was converted into the change in visual angle (1/TTC). The power exponents of the approximation curves for the constant relative velocity condition in the figure (blue line) are exactly the same as those in Table 5, because the intensity of the stimulus in terms of the closeness and that in terms of the change in visual angle were equal. Meanwhile, the power exponents of the deceleration condition were in the 1.03-1.22 range, and their correlate coefficients were in the 0.94-0.96 range. This means that when the intensity of the stimulus is defined in terms of the change in visual angle (1/TTC), the relationship between the intensity of the stimulus and the driver’s subjective estimates of the closeness of the lead car with respect to the standard stimulus was proportional for both the constant relative velocity and deceleration conditions. The power exponent is approximately 1. The differences between these results, if any, were very small among the different initial distance headway conditions.

Theoretically speaking, the power exponents of the lines for the constant relative velocity and deceleration conditions are 1 and 0.5, respectively, if the intensity of the stimulus is considered to be the closeness, while they are both 1, if the intensity of the stimulus is considered the change in visual angle (=1/TTC). (See Appendix I for the rational). The results described above very well to these theoretical predictions. These results suggest that the drivers perceived the lead car closing in terms of the visual angle, implying a tight connection between their perception and the 1/TTC as expressed in formula (1) above.

5. General Discussion

The following findings were obtained in the present study. Experiment 1 demonstrated that the 1/TTC was constant when the drivers perceived to be starting to close on the lead car, regardless of the initial distance headway for the entire range tested, which was between 20 and 60 m.

Experiment 2 demonstrated that the drivers perceived the lead car closing in terms of the change in visual angle (=1/TTC, 1/τ), suggesting a tight connection between their perception and the 1/TTC as expressed in formula (1).

Many studies (16)-(19) have attempted to quantify TTC perception over the years. Caird et al. (20), Manser et al. (21) and Cavallo et al. (22) compared the outcomes of these studies, showing that the subjective estimates of the TTC are underestimated in most, if not all, cases. The present study, by contrast, demonstrated that the drivers’ estimates were accurate for the TTC perception of the lead car closing. The difference between the previous studies and the present one can be attributed to the experimental protocol and theory about visual stimuli.

Let us start discussing the experimental protocol. This study was designed to directly measure the perception. Experiment 2 confirmed the linear relationship between the 1/TTC and the driver’s subjective evaluation of closeness of the lead car by using a magnitude estimation method, while experiments 1 accurately determined that the drivers perceived when the lead car starts closing in terms of 1/TTC, by subtracting the response time of each of the participants from their data. If the response times were not taken into consideration, the 1/TTC would have looked underestimated by approximately 0.5 sec., and the degree of underestimation cannot be ignored in some cases, especially when the initial distance headway is 20 m or less (Compare Figs. 4 and 5). In this sense, the present study is an attempt to elucidate the characteristics of the drivers’ perception, while the previous studies failed to achieve this because the response time, which is one of the more crucial human factors, was not taken into account. (The participants were instructed to press the button (20)-(23) or say aloud “now” (16) when they decided the closing object collided with them, where the object disappeared in the final phase of closing (i.e., Predict Motion Task). That is, PMD is absolute evaluation and Magnitude Estimation method is relative evaluation.

We now turn this discussion to the methodology for quantifying the stimuli. As mentioned above, experiment 2 in this study compared a pair of stimuli of the lead car closing to quantify the relationship between the driver’s subjective evaluation and the rate of closing (i.e., the change in visual angle). The previous studies, contrastively, consider the absolute time-to-contact between a moving object and the participants themselves as the information the driver would use. The deviations in data would be smaller for the relative evaluation method than those for the absolute evaluation method. In addition, the good correlation...
between the 1/TTC defined by the visual stimuli and the subjective evaluations in experiment 2 might be due to the relative evaluation method used in the experiment.

We would also like to emphasize the importance of the index we used, i.e., an 1/TTC, instead of a time-to-contact for the estimation of the driver’s perception. While in this study a key index was the change in visual angle (1/TTC), in the previous studies it was the “time-to-collision” (perceived by the change in visual angle\(^9\)). Since these two indices are an inverse of each other, the sensitivity for the deviations would be different. For example, the difference between 10 and 15 sec in the TTC corresponds to the difference between 0.1 and 0.07 in the change in visual angle. This difference in terms of the change in visual angle is small and insignificant, whereas the difference in time-to-collision as such is 5 sec., which may be considered a big difference.

Accurate TTC perception is said to be possible if there is 0.2-2.0 sec. of margin time for the observed\(^{14,16,24,25}\). We could directly observe the perception of the lead car closing, because we used the change in visual angle. It is doubtful, however, that the driver can convert it into the time-to-collision in the aforementioned limited margin time.

To sum up the discussion, the participants in the present study could conduct a reasonably correct evaluation of the stimuli, because of the indices we used in the analyses.

The previous studies have demonstrated the nature of TTC and its perception by looking at the way in which people react to it\(^9\). The present study, in contrast, objectively estimated the magnitude of stimuli that human subjects perceive, and quantified it as the subjective perception. The results showed that the correlation of human perception was not the actual time-to-contact with the acceleration components taken into consideration, but the visual angle (1/TTC), assuming that the relative velocity is constant.

6. Conclusion

The perception of closing on the lead car in a car-following situation can be explained in terms of the 1/TTC. The findings provide empirical evidence in support of the studies on human and animal behavior in terms of the TTC based on David Lee’s terminology.

It is said that automobile driving consist of a repetition of cognition-judgment-operation. We believe that an 1/TTC, of which we have experimentally validated the importance in cognition, is also useful in understanding the remaining processes in driving, that is, judgment and operation.

Appendix

I. Reaction time on individual

The participants were each asked to press the brake pedal as soon as the brake light of the lead car was lit prior to Experiments 2. This was meant to obtain the participants’ average reaction time to the presentation of the visual stimulus. Table 6 lists the mean and standard deviation of the response time of each participant.

II. Stimulus Intensity defined by Visual Angle Change

This section describes the definition of the stimulus intensity and the relative stimulus ratio to be used in a pairwise comparison.

The visual angle used as the stimulus intensity can be given as an 1/TTC in Eq. (2).

In what follows, the following two cases will be considered: when closing on the lead car at a constant relative velocity (Case A), and when closing on the lead car at a constant deceleration (Case B). As shown in Fig.12, in both Case A and B, the shorter the distance headway is the larger the stimulus intensity as defined in Eq. (2). For all of the conditions in Experiment 1, the visual image of the lead car is designed to disappear when the distance headway with the lead car reaches a certain point (D\(_{\text{disappearance}}\) in Fig.9). Thus, the stimulus intensity is at its greatest right before the image of the lead car vanishes. The last image of the lead car would remain as an after-image and the driver would use this after-image to estimate the extent to which they closed on the lead car.

A: When closing on lead car at constant relative velocity

The intensity of the standard stimulus (subscript “s”) and that of the target stimulus (subscript “t”) are given in Eqs. (2) and (3):

\[
\frac{1}{TTC_s} = \frac{V_r}{D_t} \quad (2)
\]

\[
\frac{1}{TTC_t} = \frac{V_r}{D_t} \quad (3)
\]

The comparison of the stimuli is to be done on a ratio scale. The ratio of the two stimuli is given in Eq. (4).

\[
\text{Ratio of Stimuli} = \left(\frac{1}{TTC_s}\right) \times \left(\frac{1}{TTC_t}\right) = \left(\frac{V_r}{D_t}\right) \times \left(\frac{V_r}{D_t}\right) = \left(\frac{V_r}{D_t}\right) \quad (4)
\]
If we assume that the comparison of the stimulus intensity is made based on the distance headway presented to the driver right before the image of the lead car disappeared, and the ratio of the standard and target stimuli can be expressed using Eq. (5) below:

\[
\text{Ratio of Stimuli} = \left( \frac{V_r}{V_t} \right)^{1/2} \quad (5)
\]

If \( V_r = 16.7 \, \text{m/s} \) and \( V_t = 11.1 \, \text{m/s} \), the ratio of the stimuli is 0.67.

B: When closing with lead car at constant deceleration

If the lead car closes at a constant deceleration rate \( a \) from the initial distance headway, the relative velocity \( V_r \) of the lead car is at \( D_t \) or \( (D_t - D) \) away from the host car given using Eq. (6):

\[
V_r = \sqrt{2a(D_t - D)} \quad (6)
\]

The 1/TTC for the standard stimulus and that for the target stimulus are given in Eqs. (7) and (8):

\[
\frac{1}{TTC} = \frac{2a(D_t - D)}{D_t} \quad (7)
\]

\[
\frac{1}{TTC} = \frac{2a(D_t - D)}{D_t} \quad (8)
\]

The comparison of the stimuli is to be done on a ratio scale. The ratio of the two stimuli is given in Eq. (9):

\[
\text{Ratio of Stimuli} = \left( \frac{1}{TTC_s} \right)^{1/2} \left( \frac{1}{TTC_t} \right)^{-1/2} D
\quad (9)
\]

If we assume that the comparison of the stimulus intensity is made based on the distance headway presented to the driver right before the image of the lead car disappeared, \( D_s = D_t = D_{\text{disappearance}} \), and then the ratio of the standard and target stimuli can be expressed in Eq. (10):

\[
\text{Ratio of Stimuli} = \left( \frac{a_s}{a_t} \right)^{1/3} \quad (10)
\]

If \( a_s = 5 \, \text{m/s}^2 \) and \( a_t = 7 \, \text{m/s}^2 \), the ratio of the stimuli is 1.18.

References

(1) ITARDA; Traffic Stadies 2009, ITARDA (2010) (in Japanese)
(2) Nissan Motor Co., Ltd. Website: http://www.nissan-global.com/EN/NEWS/2010/ STORY/100728-01-e.html
(3) T. Sawada, T. Hirose, N. Kasuga, and M. Zeniya: Study on Evaluation of Collision Mitigation Brake System, IATSS Review, Vol.33, No.4 (2008)
(4) T. Kondoh, T. Yamamura, S. Kitazaki, N. Kuge, and E.R. Boer: Identification of Visual Cues and Quantification of Drivers’ Perception of Proximity Risk to the Lead Vehicle in Car-Following Situations, Journal of Mechanical Systems for Transportation and Logistics, Vol.1, No.2, p.170-180 (2008)
(5) S. Kitajima, Y. Marumo, T. Hirooka and M. Itoh: Theoretical and Empirical Comparison about Evaluation Indices Concerning Driver’s Rear-End Collision Risk, In Proceedings of International Conference on Advanced Vehicle Control (AVEC’08), p.602-607 (2008).
(6) K. Morita: Factors with the Greatest Influence on Drivers’ Judgment of When to Apply Brakes, In Proceedings of SICE-ICASSE International Joint Conference 2005, Korea (2006).
(7) D. Lee: A Theory of Visual Control of Braking Based on Information about Time-To-Collision, Perception, Vol.5, p.437-459 (1976)
(8) Y. Akatsu: Innovative Safety Concept and Solution, SAE Conference Congress, Detroit, 2006-21-0083 (2006).
(9) J.C.F. de Winter, M. Mulder, M. M. van Paassen, D.A. Abbink, and P.A. Wieringa: A Two-Dimensional Weighting Function for a Driver Assistance System, IEEE Transactions on Systems Man and Cybernetics Part B, p.189-195 (2008)
(10) D. Lee: Visual Control of Velocity of Approach by Pigeons When Landing, Journal of Experimental Biology, 180, p.85-104 (1993)
(11) R. Lobojoi, N. Benguigui, J. Bertsch and M.P. Broderick: Collision Avoidance Behavior as a Function of Aging and Tennis Playing, Experimental Brain Research, Vol.184, No.4, p.457-468 (2008)
(12) V. Cavallo, R. Lobjois, and F. Vienne: The Interest of an Interactive Road Crossing Simulation for the Study of Adaptive road Crossing Behavior,” In Proceeding of Driving Simulation Conference Asia/Pacific 2006(CD-ROM), Japan (2006)
(13) S. S. Stenves, “On the psychophysical law,” Psychological Review, Vol. 64(3), p.153-181 (1957)
(14) J.J. Gibson: The Concept of the Stimulus in Psychology, American Psychologist, Vol.15, p.694-704 (1960)
(15) D. Lee, D. Young, P. Reddish, S. Lough and T. Clayton: Visual Timing in Hitting an Accelerating Ball, Quarterly Journal of Experimental Psychology, 35A, p.333-346 (1983)
(16) D. McLread and E. Ross: Optic-flow and Cognitive Factors in Time-to-collision Estimates, Perception, Vol.12, p.417-423 (1983)
(17) V. Cavallo, and M. Laurent: Visual Information and Skill Level in Time-to-collision Estimation, Perception, Vol.17, p.623-632 (1988)
(18) A. Recarte, L. Nune, & J. Lillo: Estimation of Time-to-Arrival in a Real Vehicle and in a Simulation Task: Effects of Sex, Driving Experience, Speed and Distance, Vision in Vehicles V (1996).
(19) R. Sidaway, M. Fairweather, H. Sekiya, and J. McNitt-Gray: Time-to-Collision Estimation in a Simulated Driving Task, Human Factors, Vol. 38, No.1, p.101-113 (1996)
(20) K. Caird & P. Hancock: The Perception of Arrival Time for Different Oncoming Vehicles at an Intersection, Ecological Psychology, Vol. 6, p.83-109 (1994)
(21) M. Manser and P. Hancock: Influence of Approach Angle on Estimates of Time-to-contact, Ecological Psychology, Vol. 8, p.71-99 (1996).
(22) V. Cavallo, D. Mestre, and C. Berthelon: Time-to-Collision Judgements: Visual and Spatio-temporal Factors, Traffic and Transport Psychology: Theory and Application, p.97-111 (1997).
(23) M. K. Kaiser and H. Hecht: Time-to-passage Judgments in Non-constant Optical Flow Fields, Perception & Psychophysics, 57, p.817–825 (1995)
(24) R. Kiefer, A. Flannagan, and J. Jerome: Time-to-collision Judgments under Realistic Driving Conditions, Human Factors, Vol. 48, No. 2, summer 2006, p.334-345 (2006)
(25) D. Lee and D. Young: Visual Timing of Interactive Action, in Ingle et al. (eds.), Brain Mechanism and Spatial Vision, Kluwer Academic Publishers.