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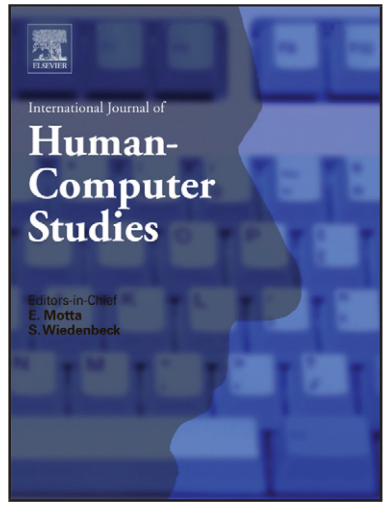

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An Empirical Investigation of a Dynamic Brake Light Concept for Reduction of Rear-end Collisions through Manipulation of Optical Looming

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Abstract

The concept of dynamically manipulating the optical looming cues of a lead vehicle's brake lights is investigated as a means of potentially reducing the frequency of rear-end collisions in automobile driving. In a low-fidelity driving simulator, 40 participants were instructed to follow a leading vehicle (LV) and appropriately respond to braking of the LV, under three visibility conditions: day, night-time with following vehicle (FV) headlights, and night-time without FV headlights. During some LV braking events, separation and size of the brake lights of the LV were expanded or contracted, by a nominally imperceptible amount, to simulate an *effective virtual time shift* in the headway of the LV. Results show that this manipulation was most effective for very poor visibility conditions: at night with no headlights, for which LV brake lights were most salient. When confronting a LV with expanding or contracting brake lights, subjects generally braked sooner or later respectively, in comparison with the no manipulation case. The concept shows some promise for causing drivers to brake sooner in emergencies.

Keywords: optical looming; rear-end collision; emergency braking; dynamic brake lights

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1. Introduction

This paper introduces a proof-of-concept study that aims to reduce the high rate of rear-end collisions, which contribute to an increasingly large number of crashes in automobile driving. The concept is a *dynamic brake light system*, which would serve to trigger faster braking reactions from following drivers (FDs) responding to hard braking leading vehicles (LVs), by means of expanding the size and separation of the brake lights of the LV during braking. The study was designed with the intention that, if this concept were found effective at positively affecting subjects' braking behaviour in response to emergency braking LVs on a simulated roadway, the results of the study could provide the basis for seriously considering such brake lights in future rear signalling applications.

1.1. Rear-end collision accidents: consequences

According to U.S. National Highway Traffic Safety Association (NHTSA, 2005), in 2003 alone rear-end collisions accounted for 30% of all crashes (1.9 million) and caused 5.4% of total fatal crashes (2,076), 29.6% of all injury crashes (0.57 million), and 29.8% of all property-damage-only crashes (1.3 million). The major causal factor of rear-end collisions occurs when the FD does not react correctly to the behaviour of the LV, due to either inadequate or late detection of LV deceleration. This has been attributed variously to factors such as inattention, inadequate perceptual discrimination, incorrect interpretation about traffic movements, or inadequate headway to allow the FD to react appropriately to emergency braking by the LV (Rumar, 1990; Knipling et. al., 1993; Kostyniuk & Eby, 1998).

1.2. Emergency braking

Although current 'binary' brake light systems indicate whenever the driver of a LV has a foot on the brake – thereby immeasurably assisting in *detection* of LV deceleration– this information is frequently insufficient for helping the FD to properly judge the *rate* of deceleration. For such judgements as when to brake, how hard to brake, or whether it is necessary to brake at all, drivers have to rely on direct visual information about how rapidly the FV is closing in on the LV (Liebermann, 1995). Whereas under most circumstances such directly perceived visual information may be adequate, in extreme situations such as emergency LV braking it is clearly not adequate, because there is always a danger that the FD might be dangerously too close to the LV before he is able to pick up adequate closing information.

The braking response – moving the foot to the brake pedal – is only the first stage; the braking *adjustment* stage is just as critical. Normally a FD does not initiate full-power braking as soon as he ascertains that a LV is braking since, among other things, this would risk a skid and/or being run into from behind. Rather, drivers normally adjust their braking on the basis of the perceived urgency of a situation. In an emergency, for example, it is important, and often critical, to adjust braking to an appropriate level early enough to avoid rear-end collisions, because the sooner deceleration is initiated, the more effective it is. Therefore, whenever the LV brakes very hard, and/or when lead distances are very short, any supplemental information that will allow the FD to control his braking profile appropriately should be of obvious benefit.

1.3. Rear signalling improvements

Much consideration has been given to whether, and how, the intensity of a LV braking manoeuvre can be indicated to the traffic behind, including a number of proposals for informing the FD about braking emergencies through LV rear signal enhancement. One example is the *advanced braking warning system* (Shinar, 2000), which activates LV brake lights in an anticipatory fashion whenever the lead driver (LD) suddenly removes his foot from the accelerator pedal while going at high speeds, prior to actually applying any pressure on the brake pedal. Another example is the addition of an *imperative brake light signal* on the rear of the vehicle (Tang, 1989), which would light up only when the emergency brake is activated. Another suggestion is *flashing lights,* which either would communicate the deceleration rate of the LV to the FD – i.e. gentle stops would produce slow flashes and rapid stops rapid flashes (Voevodsky, 1974) – or would indicate sharp decelerations of the LV to the FD by switching on additional flashing lamps – such as centre high mounted brake lights (Horowitz, 1994; Browne & Chin, 1991), rear fog lamps, stop lamps, and hazard warning signals (Alferdinck, 2004). Gail et al (2001) suggested a *two-stage brake force display*, for which the area and luminance of LV brake lights would change from a normally small area and low luminance to a larger area, higher luminance state for any LV deceleration rate greater than 7 m/s^2.

These examples share the common concept of communicating an emergent situation explicitly to the FD so that he can immediately be aware that the brakes of the LV have been applied in an (apparent) emergency. One potential disadvantage of such systems, however, is that detection and comprehension of a warning in these settings could be distracting or even time-consuming, in the sense that FD would have even more information to process in times of emergency. Moreover, it would not be unexpected for a significant number of FDs to adjust their subjective acceptable risk thresholds (Wilde, 1982) to accommodate to what they perceive to be the operational properties of such emergency braking systems, after having encountered them in action a number of times during driving. With these considerations in mind, we propose that an ideal system would be one for which the FD would be *unaware* that he is being warned to brake more rapidly, but would nevertheless be compelled do so – involuntarily so to speak.

1.4. Perception of time-to-collision (TTC) derived from optical looming cues

Time-to-collision (TTC) is the time remaining to a collision when approaching a stationary or moving object, assuming that the vehicle's direction and closing velocity will remain constant. (We can therefore define TTC = X_{rel}/V_{rel}, where X_{rel} is relative separation between vehicles and V_{rel} is the relative velocity.) Based on Lee’s (1976) seminal work, *optical looming*, which is defined as the symmetrical expansion of the retinal image size of an approaching object on a collision course, can specify TTC through an optic variable *Tau*, defined as the *inverse of the relative expansion rate of the retinal image*, assuming a constant closing velocity. Lee argued that TTC information, directly specified through Tau, could in principle be used to judge when to start braking and how to control braking. In other words, a driver could initiate braking at a certain Tau margin and control braking simply on the basis of the rate of change of Tau. Lee's hypothesis about the use of Tau through optical looming during automobile driving has been supported by experimental evidence (van der Horst, 1990, 1991; van Winsum & Heino, 1996).

In our own simulated car driving experiments, we have also found a direct relationship between optical looming cues and control of braking (Li & Milgram, 2004a; 2005). In those experiments FDs were found to advance or delay their braking behaviour in a predictable fashion while following a size-changing LV whose optical image was experimentally manipulated. The hypothesis supported in those studies was that, when the FD brakes sooner in response to an expanding LV (or later to a contracting LV), this behaviour is a result of manipulation of the optical looming cue. Similar patterns of behaviour have been observed also for other psychomotor tasks, for example in animal studies (Sun, Carey & Goodale, 1992), for ball catching involving dynamic size changing (Savelsbergh et al., 1991; 1993; van der Kamp, 1999; Wann & Rushton, 1995a), and for braking while approaching a size-changing barrier in a bicycle simulator (Sun & Frost, 1998).

1.5. Dynamic brake light concept

In actual driving situations there is no obvious way to manipulate the size of a real LV, as can be done with a virtual vehicle in a driving simulator. Research has shown, however, that the brake lights of a LV are a very important source of information for FDs to regulate speed and inter-vehicle distance, on the basis of changes in the perceived distance between LV brake lights. This is especially true during reduced visibility situations, such as night time, fog and rainy weather (Janssen et al, 1976; Liebermann et al, 1995). Theoretically then, it should be possible to manipulate the optical looming of the image formed by the LV brake lights, in order to shorten the FD's perception of TTC with the LV and cause him to brake sooner.

With this in mind, a *dynamic automobile brake light system* has been proposed, as a means of potentially reducing the rate of occurrence of rear-end collisions (Li & Milgram, 2004b). According to that proposal, whenever the LV brakes rapidly (assuming that sensors within the lead vehicle can detect and estimate following vehicle distance), both the *separation* and *size* of the brake lights of the LV will automatically expand, *continuously and gradually,* to amplify the natural optical looming which occurs to the FD during braking. The proposed concept is based on the hypothesis that exaggerating the apparent rate of optical looming whenever a LV brakes very hard, and/or when lead distances become very short, will provide the FD with the intuitive illusion of an (artificially) more rapidly approaching LV, which may then subconsciously prompt the FD to decelerate more quickly. Clearly, a decrease of even a few tens of milliseconds in braking time could have a significant impact on overall traffic safety, when aggregated over the extremely large number of FV braking incidents.

Other successful applications of turning human visual illusions or distortions to advantage in order to improve transportation safety do exist. One of these is the redesign of a dangerous traffic circle in Scotland, where drivers had tended to overspeed, with a high accident rate as a consequence (Denton, 1980). Lines of diminishing separation were drawn across the roadway to “trick” the driver’s perceptual system; whenever approaching the circle at an excessive speed, drivers would experience the “flow” of transverse line texture passing the vehicle as signalling an amplification in speed. Because of the essentially automatic nature of such percepts, it was predicted that drivers would instinctively brake in response to the augmented speed percept, bringing it to within a safer range. This is exactly the effect that was observed after the marked pavement was introduced, resulting in a substantial reduction in fatal accidents at that traffic circle, a result that has been sustained for several years (Godley, 1997).

The objective of the experiment reported here was to empirically investigate whether and how the dynamic brake light concept described above might influence drivers' braking behaviour, in a manner similar to the marked pavement described above. Specifically, using a low-fidelity diving simulator, we have investigated whether manipulating the separation and size of the brake lights of the LV while it is decelerating can make FDs modify their braking behaviour accordingly. In addition, to ascertain whether such a phenomenon, if observed, might be a consequence simply of the *presence* of our manipulation, rather than of its prescribed pattern, our experiment comprises manipulations in both directions, that is, *both expansion and contraction* (even though any practical operational system would logically comprise only expansion), and at two levels for each. Our hypotheses are thus: (i) that significant effects on FD braking behaviour can be expected through manipulation of only brake lights; (ii) that LV brake light expansion will cause advanced braking, while contraction will retard braking; and (iii) that modifying the magnitude of the manipulation will cause changes in braking behaviour which correspond to the size of the manipulation. A fourth aspect of our investigation involved a comparison of daytime versus night-time driving, under different illumination conditions, with the hypothesis being (iv) that manipulation of the brake light optical looming properties will have its greatest impact for lowest visibility conditions, for which the brake light cue is most relevant for assisting in FD braking.

2. Method

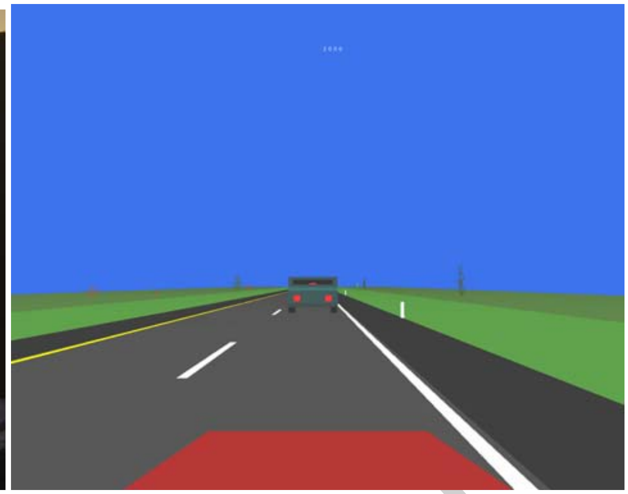
2.1. Participants

Forty male paid volunteers participated in the experiment. They were 18-36 years old (mean=24; SD=5.1) with normal or corrected-to-normal vision and naïve to the purpose of the experiment. All had full driving licenses, with 3-15 years of driving experience (mean=6; SD=3.3). Our reason for limiting the subject population to young male drivers was to give more power to our experiment, by allowing us to focus on the optical cue manipulation factor. In doing so, any existing significant differences in braking behaviour between manipulation and no manipulation conditions could be more easily identified, without other variances caused by gender or age.

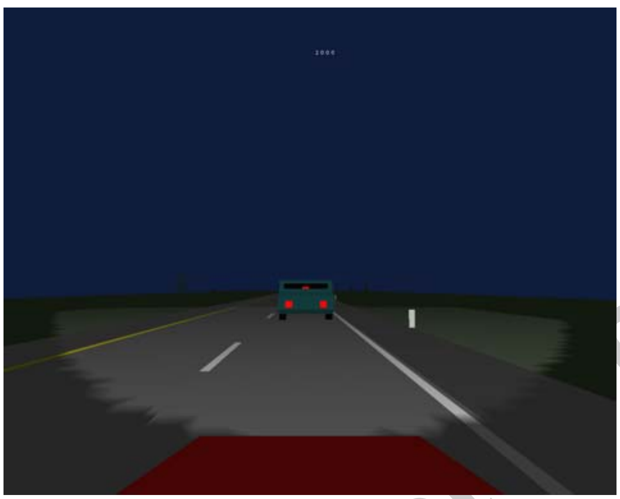
2.2. Apparatus

Experiments were conducted using a low-fidelity driving simulator, developed by York Computer Technologies of Kingston, Ontario, running on a PC under Windows XP. The roadway scene was projected onto a large screen (150 x 110 cm) at a distance of 200 cm from the subjects, using a commercial LCD projector (LitePro 620, Infocus Systems). The steering wheel and gas/brake pedal was a WingMan Formula Force GP from Logitech, a standard game control device. Figure 1a shows a photograph of the experimental setup. Figures 1b, 1c and 1d show sample scenes for the three scenarios corresponding to the three visibility conditions for this experiment: *day time*, *night-time <u>with</u> FV headlights,* and *night-time <u>without</u> FV headlights*.

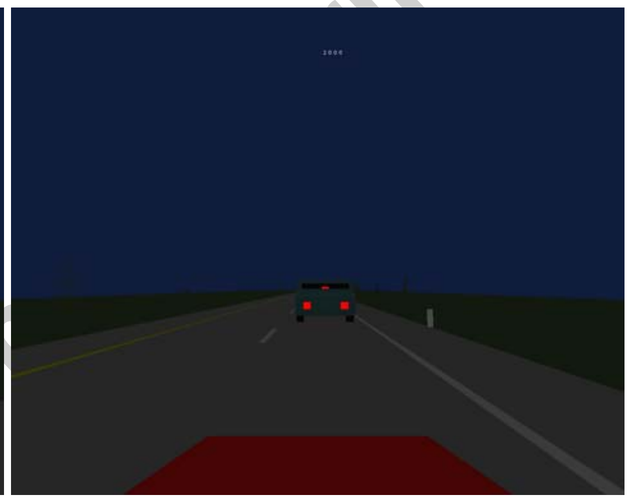
a: Photograph of the experimental setup



b: Day time view



c: Night-time view, with FV headlights



d: Night-time view without FV headlights

Figure 1. (a) Photograph of the experimental setup. (Note that the ceiling lights were turned off during the real experiments.) (b, c, d) Experimental scenes for the three vehicle following conditions. The shape at the bottom is the hood of the following vehicle.

2.3. Task

Subjects were instructed to "safely follow" (i.e. without overtaking) a LV at a required following distance (33 m) on a simulated straight highway, and to “appropriately respond” to braking of the LV, just as they would "under real driving conditions". Subjects could control speed, steering, and braking. Some simulated sound of the subjects' own vehicle engine was provided, with a frequency that varied with the vehicle’s speed. A screeching sound would also be triggered whenever the FV braked very hard (deceleration rate ≥ 10 m/s^2).

In order precisely to control our primary independent variable, effective virtual time shift (explained below), it was ideally necessary to initiate each LV braking event at a consistent value of following distance and relative velocity. In particular, the nominal speed of the LV was set at

80 km/h, which meant that, with a nominal following distance of 33 m, our aim was to maintain a time gap of 1.5 s on the drivers during the car following phase of the experiment. Unfortunately, however, if we had simply imposed these two conditions by holding them constant, that would have meant that the experimental subjects (the FDs) would have had nothing to do but watch for LV braking events – that is, our experiment would have turned into a simple reaction time experiment instead of a simulated driving task. To counter this, whenever subject controlled following distances went beyond the 33 ±10m range, an audible message of *"Too far!"* was heard when the following vehicle was too far behind the LV (>43m), and conversely, whenever the gap became too small (<23m), they were told *"Too close!"*. (A somewhat complex algorithm, not explained here, was used to regulate LV speed; subjects were unaware of the details of this speed regulation.) As stated above, because we wanted LV braking to commence only when the intervehicle time gap was 1.5s, braking events were triggered only when LV speed was 80 km/h, following vehicle speed was within the range 77-83 km/h (80±3), and following distance was between 32 and 34 m (±1m). This corresponded, therefore, to a permitted range of time gaps of 1.4 - 1.6 s.

Further to the comment above regarding our aim that this experiment not merely involve sudden responses to each braking event, a range of different LV deceleration rates was used, to discourage subjects from simply braking as hard as possible to every LV braking event. The intention was that, whereas rapid braking would be appropriate for rapid LV deceleration, much slower braking was expected for lower LV deceleration rates. ('Perfect' braking performance, therefore, would have meant that relative vehicle velocity would remain constant (=0) throughout the braking event, with both vehicles decelerating at identical rates.) A number of indices of performance were imposed, in an attempt to elicit desirable braking behaviour. One corresponded to 'excessive braking', caused by the following distance becoming too great (defined as exceeding 1.1 x required following distance) during a braking event. Whenever this happened, a voice message declared *"Excessive Braking!"* The opposite case of 'insufficient braking' was manifested obviously in the form of a rear-end collision. Using a point system, whereby subjects were allocated 2000 points at the beginning of each trial, every time they received a voice message (i.e. "too far" or "too close") during following, 20 points were deducted. Furthermore, for every second subjects strayed from the right lane (i.e. into the left lane or off the right edge of the road), another 20 points were lost. For every "excessive braking" profile, and for every "rear-end collision" event, subjects were docked 200 and 500 points respectively. These points were averaged over trials and, based on the total points accumulated, a monetary bonus was awarded, to motivate subjects to follow the instructions.

2.4. Procedure

At the beginning of each trial, a simulated vehicle would pass the subject's own vehicle in the left lane, move to the right lane ahead, and then become the LV. During the ensuing trial, the LV braked 20 times, at randomly distributed intervals, and at one of 4 different deceleration rates, accompanied by one of 5 different ways of manipulating the separation and size of the brake lights of the LV. The deceleration rates were divided into two categories, consisting of one *low rate* {4 m/s^2} and three *high rates* {6, 8, 10 m/s^2}. During high rates of deceleration, the LV slowed to a complete stop, but during low deceleration the LV slowed to only 60 km/h. In both cases the LV commenced reaccelerating (to 80 km/h) 2 seconds later. The low deceleration rates were thus intended to provide a set of distracting events, to prevent subjects from simply habituating to hard braking.

The study was conducted in one session for each subject. Participants first filled out a demographic questionnaire and received both written and oral instructions describing the experimental platform and the task. This was followed by 3 training trials – one for each of the 3 viewing conditions – and 9 real trials – 3 for each of the 3 viewing conditions. Each trial lasted about 10 minutes, with the whole experiment lasting about 2.5 hours, including breaks between trials. Manipulation conditions and deceleration rates were randomised for every trial, and the order of presentation of trials was counterbalanced across participants. At the end of the experiment, participants filled out a questionnaire which probed the strategies used for following and braking. Feedback was also solicited about their impression of the experiment and the simulator.

2.5. Manipulation of the optical looming cue through size and separation of the brake lights

During some of the braking events, while the LV was braking the size of the *brake light triangle (BLT)* formed by the two bottom brake lights and the one high centre brake light of the LV was manipulated continuously, in one of two directions: expansion or contraction, as illustrated in Figure 2. (In theory, it would have been possible to conduct the experiment using only the two bottom brake lights, instead of the three lights forming the BLT; however, our expectation is that this would have generated weaker results, and thus was not chosen for our initial investigation.)

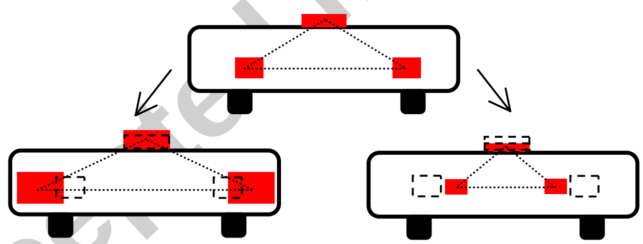


Figure 2. Rear view sketch of LV, showing manipulation of separation and size of the brake lights during LV braking. Top represents normal pattern of brake lights. Bottom left illustrates expanded brake lights and bottom right represents contracted brake lights. Normal (top) pattern is shown for comparison as dashed lines. Note that only initial and final stages are shown here; the actual manipulation involves a *continuous* process during braking.

The magnitude of the size change of the BLT image was designed to mimic the expansion of the retinal images of the same triangle, of constant size, *as if* the array of lights were located behind (while expanding) or in front of (while contracting) its actual position – i.e. closer to or further away from the FD. Note that *only the rate of change of size (optical looming) of the BLT, not its actual position, was manipulated*. This was done at one of two levels: 0.2s and 0.4s of *effective virtual time shift* ($\Delta TTC_{virtual}$), i.e. producing TTC values due to optical looming which should theoretically be perceived as being shifted by either 0.2s or 0.4s respectively.

Figure 3 is a schematic illustration of how the size of an approaching target object, such as the BLT, can be manipulated, using the Tau principle, to appear to be either closer to or further away ***in time*** from an observer.

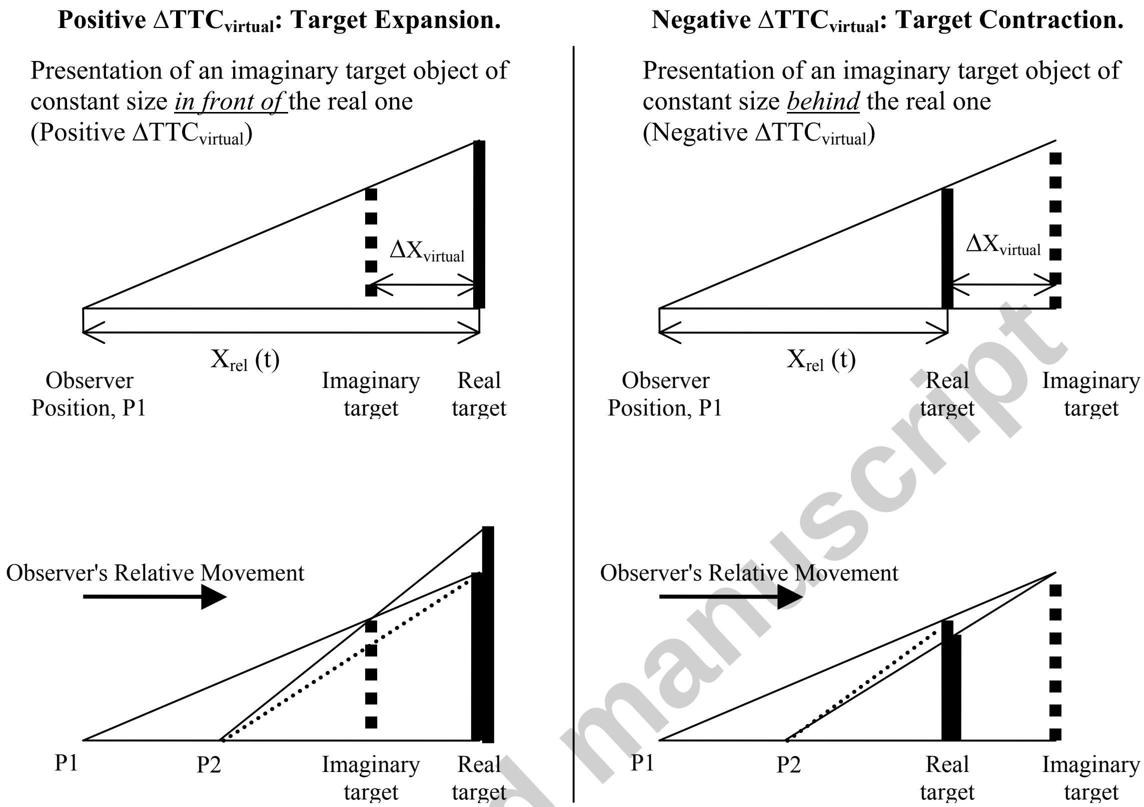


Figure 3. Illustration of Effective Virtual Time Shift.
Left side, top figure: If (imaginary) target object of height indicated by dashed line were located at position indicated, at a distance $\Delta X_{virtual}$ in front of real target, it would subtend the same visual angle on the observer's retina as the corresponding real target. In other words, the dashed object could be perceived as either of the same size and at the same position as the real target, or smaller and closer. Bottom left figure shows that, as observer moves from position P1 to P2, the visual angle of the real target should increase, as shown by the dotted line. However, if during the movement from P1 to P2 the size of the real target were instead to *expand*, to the extent that its visual angle matched that of the (constant sized) imaginary object (dashed line), the real target object would be perceived as being *closer* to the observer (in both space and time), compatible with the location of the imaginary object, even though its actual location has not changed. $\Delta X_{virtual}$ is therefore the *virtual (or effective) offset distance* between the imaginary and real target positions, corresponding to a *virtual shift in time*, $\Delta TTC_{virtual}$. For a constant value of $\Delta TTC_{virtual}$, $\Delta X_{virtual}$ must change with time, and vice versa for constant $\Delta X_{virtual}$.
Right side (contraction): Analogous to left side, but for effective *negative* shift in $\Delta TTC_{virtual}$.

To realise the effective virtual time shift – which was implemented *in real time* during braking – the software continuously recomputed the geometric size of the BLT, and its image was then *scaled* in accordance with the imposed $\Delta TTC_{virtual}$ value. As explained in Figure 3, the present experiment assumed a constant value of $\Delta TTC_{virtual}$, which meant that it was necessary to recompute the variable $X_{virtual}(t)$ continually. (This was in contrast to an earlier investigation (Li & Milgram, 2004a), in which we used a constant effective offset distance $X_{virtual}$ as our independent variable, which thus resulted in time varying values of $\Delta TTC_{virtual}(t)$.) The algorithm involved scaling the rendered array of brake lights by a factor R(t), which was recomputed for each frame according to (Wann & Rushton, 1995b; Li & Milgram, 2004b):

$$\begin{aligned} R(t) &= X_{rel}(t) / (X_{rel}(t) - X_{virtual}(t)) \\ &= X_{rel}(t) / (X_{rel}(t) - V_{rel}(t) \times \Delta TTC_{virtual}) \qquad (1) \end{aligned}$$

- $\Delta TTC_{virtual}$ is the desired time manipulation. Positive or negative values of $\Delta TTC_{virtual}$ produce the effect during braking of the BLT being perceived to be displaced, respectively, either closer to or further away from the FV;
- $X_{rel}(t)$ is the instantaneous distance between the FD's viewpoint and the rear of the LV;
- $V_{rel}(t)$ is the velocity of FD relative to LV. R(t) was updated only when $V_{rel}(t)>0$, that is, whenever the FD was closing in on the LV;
- $X_{virtual}(t) = V_{rel}(t) * \Delta TTC_{virtual}$ is the *effective offset distance,* or (continuously changing) *virtual distance* corresponding to the BLT's optical expansion. Positive or negative values of $X_{virtual}(t)$ correspond to the effect, respectively, of the BLT being displaced to be either closer to or further away from the FV during braking.

Reiterating, the BLT was not really displaced by the distance $\Delta X_{virtual}(t)$; *only its rate of change of size was changed*, resulting in a (constant) *virtual time shift,* $\Delta TTC_{virtual}$.

How much the size of the BLT was manipulated, R(t), depended not only on the independent variable $\Delta TTC_{virtual}$, but also on the continuously changing $V_{rel}(t)$. During a typical braking event in this experiment, $V_{rel}(t)$ gradually increases from approximately zero, when the LV starts to brake and the FD starts to respond (recall that a LV braking event was triggered only when the following vehicle speed was within ±3 km/h of the LV speed of 80 km/h), then gradually decreases to zero whenever the FD successfully brakes behind the stopped LV. Consequently, from Equation 1, during a typical braking event for $\Delta TTC_{virtual}>0$, R(t) gradually increases (hence an *expansion event*) from 1 (i.e. the original, normal size of the LV) when the LV starts to brake, then gradually return to 1 whenever the FD successfully brakes behind the stopped LV ($X_{rel}(t)>0$). Conversely, for $\Delta TTC_{virtual}<0$, R(t) starts at 1, then decreases (hence a *contraction event*), and eventually returns to 1 for successful braking. On the other hand, whenever a rear-end collision occurred, the size of the LV would be restored to its original, normal size (R(t)=1) and the experimental scenario would start over.

Figure 4 shows qualitatively both how the size of the BLT was manipulated during successful braking based on the R(t) formula, and also how the corresponding retinal image size of the BLT on the eye changed, for positive, negative and zero values of $\Delta TTC_{virtual}$.

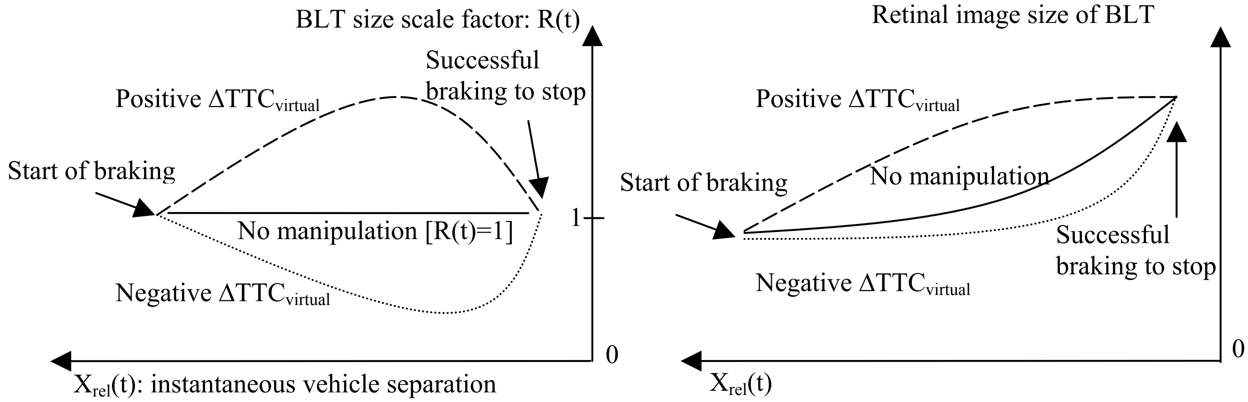


Figure 4. Qualitative illustration of changes of scale factor and retinal image size versus vehicle separation during LV braking. Left: BLT size manipulation based on $\Delta TTC_{virtual}$; right: retinal expansion of BLT on eye of the FD while LV is braking. Solid lines represent no manipulation; dashed lines represent expansion; dotted lines represent contraction. Note: R(t)=1 represents original, normal size of LV.

In designing the experiment, $\Delta TTC_{virtual}$ had to be chosen to be not too small, so as to increase the probability of observing an effect, but not too large, so as to ensure that the manipulation remained imperceptible. Taking into account the possible range of $V_{rel}(t)$ values, given the constraints of this experiment, five levels of manipulation of $\Delta TTC_{virtual}$ were used: 0s, ±0.2s, ±0.4s. In other words, negative values corresponded to retarding optical looming (LV effectively farther away), positive values to advancing displacement (LV effectively closer), and 0s to no manipulation. Our reasoning in this design was that, if expanding the BLT during braking were to reduce perception of TTC, the subjects should generally brake sooner on expansion events, and the opposite should occur for contraction events, relative to no manipulation events. In addition, the magnitude of any effects observed should correspond to the magnitude of manipulation, with proportionately larger effects for 0.4s relative to 0.2s manipulations.

In addition to the above, careful attention was paid to potential interactions between the brake lights and the rear of the LV. In order to reduce the chance of any conspicuous distortions of the manipulated BLT array occurring relative to the rear of the LV, the largest (for expansion) and smallest (for contraction) values of scaling factor R(t) were limited to 4/3 and 2/3 respectively, as determined during pilot studies.

Furthermore, as stated earlier, it was reasoned that the effect of manipulations should be more pronounced whenever the brake lights are comparatively more salient, and thus more pertinent. Consequently, three illumination conditions were compared: daytime, night-time with following vehicle (FV) headlights, and night-time without FV headlights, the hypothesis being that any effects of the optical looming manipulations would increase in that order.

2.6. Data analysis

Table 1 lists all independent and dependent variables. For all dependent variables, the time origin was taken at the instant of LV braking. Results were tested using analysis of variance (ANOVA), with an effect considered significant whenever the probability of a Type I error was lower than 1% ($p<0.01$). A three-way within-subjects ANOVA was first performed on each dependent variable, with viewing condition, manipulation, and deceleration rate as the main factors. (Only the three high deceleration, or emergency braking, events were analyzed, as the others served only as distractors). This was followed by 3 two-way within-subjects ANOVAs (manipulation x deceleration rate) for the 3 viewing conditions, and then, if significant main effects were found, 9 one-way within-subjects ANOVAs (manipulation) for the 3 viewing conditions and 3 deceleration rates. Since the factor of manipulation was the most interesting for our objective, the results presented in the following section focus on the effect of manipulation under three viewing conditions and three deceleration rates. Only results for significant effects are given.

Table 1. Independent and dependent variables

Independent Variables	Viewing Conditions {Day time, Night-time with FV headlights and Night time without FV headlights}
	Deceleration Rates of the LV {$6m/s^2$; $8m/s^2$; $10m/s^2$}
	Levels of Manipulation ($\Delta TTC_{virtual}$) {-0.4s, -0.2s, 0s, 0.2s, 0.4s}
Dependent Variables (measured during subjects' braking, with 40ms resolution)	Time of (completely) taking foot off gas pedal
	Time of (first) pressing brake pedal
	Time of maximum braking force
	Maximum braking force
	Maximum velocity difference (defined as velocity of FV minus velocity of LV)
	Minimum following distance
	Minimum time-to-collision

3. Results

3.1. Time of taking foot off gas pedal and time of first pressing brake pedal

Referring to the top of Figure 5, for *time of first taking foot off gas pedal*, a three-way within-subjects ANOVA (viewing condition x manipulation x deceleration rate) indicated only a significant viewing condition main effect ($F(2,118)=30.9$, $p<0.001$), without any two-way or three-way interactions among viewing condition, deceleration rate and manipulation. Generally, it seems that subjects released the gas pedal later in the night-time viewing condition with FV headlights. The absence of any other effects suggests that expanding (0.2 and 0.4s) or contracting (-0.2 and -0.4s) the separation and size of the brake lights of the LV during its braking did not affect the releasing of the gas pedal over any of the 3 viewing conditions or 3 deceleration rates.

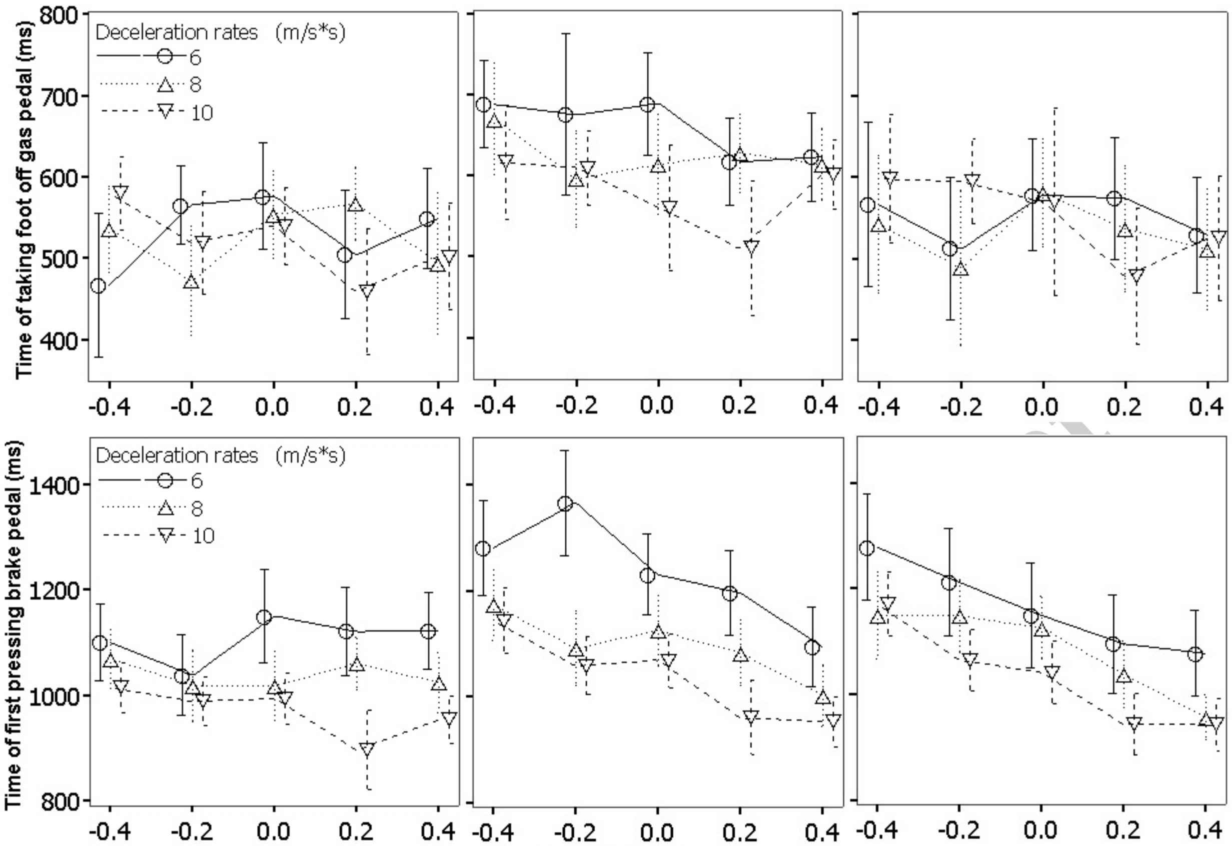


Figure 5. Top: Time of taking foot off gas pedal; bottom: time of first pressing brake pedal (both in ms). In all graphs, data are averaged across 3 viewing conditions and 3 deceleration rates, under 5 manipulation conditions. Error bars represent 95% confidence intervals. Positive, zero and negative times represent after, at, and before the start of LV braking.

On the other hand, as indicated along the bottom of Figure 5, LV brake light manipulation did apparently affect braking in terms of *time of first pressing brake pedal* during night-time but not day driving conditions. A 3-way within-subjects ANOVA (viewing condition x manipulation x deceleration rate) indicated a significant viewing condition main effect ($F(2,118)=14.7$, $p<0.001$), a significant deceleration rate main effect ($F(2,118)=59.3$, $p<0.001$), and a significant $\Delta TTC_{virtual}$ manipulation main effect ($F(4,116)=31.7$, $p<0.001$), with a significant interaction between viewing condition and $\Delta TTC_{virtual}$ manipulation only. Three follow-up 2-way within-subjects ANOVAs (manipulation x deceleration rate) were conducted for each viewing condition, revealing significant $\Delta TTC_{virtual}$ manipulation main effects only for night-time with ($F(4,116)=21.5$, $p<0.001$) and without ($F(4,116)=13.8$, $p<0.001$) headlights conditions, with neither interacting with deceleration rate.

3.2. Time of maximum braking force and maximum braking force

Referring to the top of Figure 6, for *time of maximum braking force*, a 3-way within-subjects ANOVA (viewing condition x manipulation x deceleration rate) indicated a significant viewing condition main effect ($F(2,118)=31.1$, $p<0.001$), a significant deceleration rate main effect ($F(2,118)=76.1$, $p<0.001$), and a significant $\Delta TTC_{virtual}$ manipulation main effect ($F(4,116)=13$, $p<0.001$) with a significant interaction between viewing condition and manipulation only. Three subsequent 2-way within-subjects ANOVAs (manipulation x deceleration rate) were conducted for each viewing condition separately, revealing a significant $\Delta TTC_{virtual}$ manipulation main effect only for night-time without headlights conditions ($F(4,116)=17.9$, $p<0.001$), with no interaction with deceleration rate.

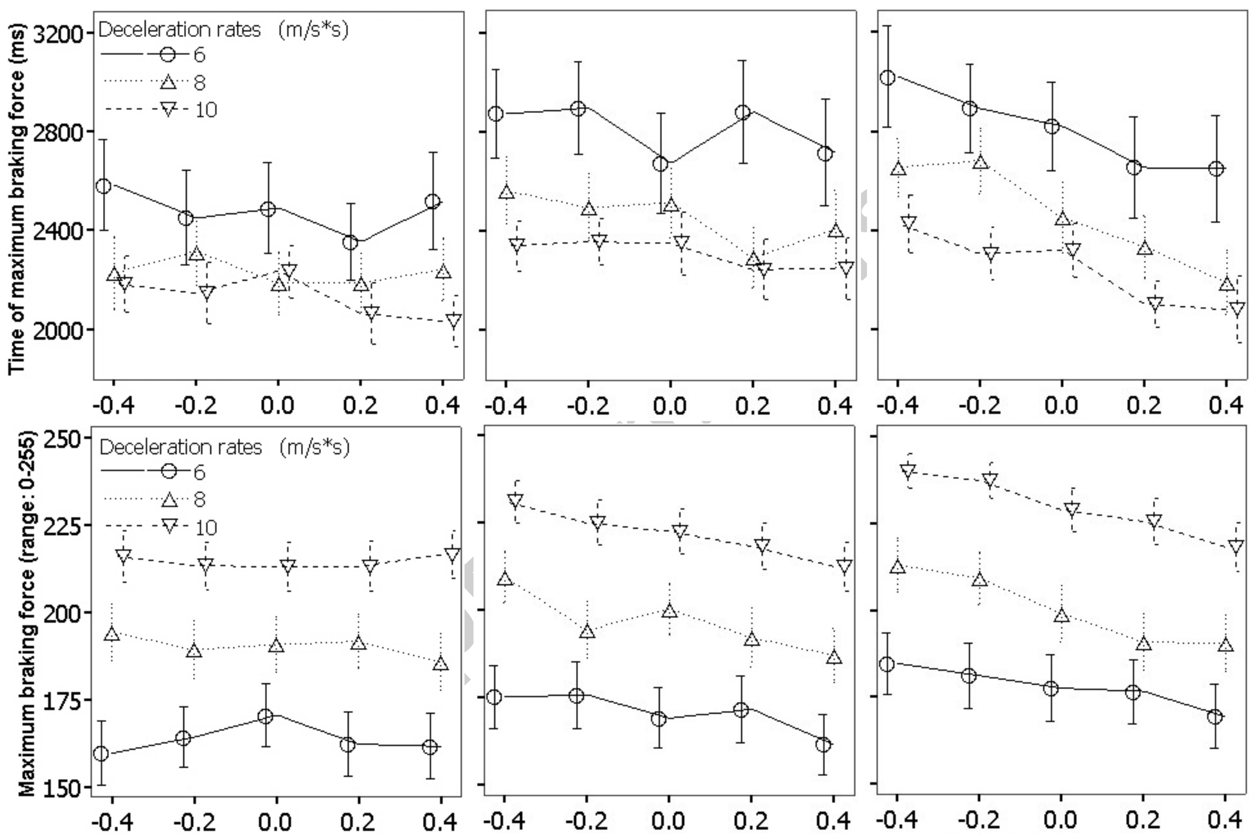


Figure 6. Top: Time of maximum braking force (in ms) and bottom: maximum braking force (range is 0 to 255).

For magnitude of *maximum braking force*, a 3-way within-subjects ANOVA (viewing condition x manipulation x deceleration rate) indicated a significant viewing condition main effect ($F(2,118)=27.3$, $p<0.001$), a significant deceleration rate main effect ($F(2,118)=357$, $p<0.001$), and a significant $\Delta TTC_{virtual}$ manipulation main effect ($F(4,116)=31.9$, $p<0.001$) with a significant interaction between viewing condition and manipulation only. Similarly, three subsequent 2-way within-subject ANOVAs (manipulation x deceleration rate) were conducted for each viewing condition, revealing significant manipulation main effects only for night-time with ($F(4,116)=14.9$, $p<0.001$) and without ($F(4,116)=21.1$, $p<0.001$) headlights conditions, with neither interacting with deceleration rate.

In summary, as shown in Figure 6, for the *daytime scenario* the $\Delta TTC_{virtual}$ manipulation did not produce any significant differences for either dependent variable for any of the three deceleration rates. For the *night-time with headlights* condition, there was also no significant effect of $\Delta TTC_{virtual}$ manipulation for time of maximum braking force; however, a significant manipulation main effect was found for maximum braking force. This suggests that during simulated driving at night with headlights, although the manipulation did not cause subjects to brake to maximum braking force earlier (for expansion) or later (for contraction), it did reduce (for expansion) or increase (for contraction) the maximum braking force (respectively less or more harsh braking). Referring back to Figure 5, this appears to be due to respectively earlier or later commencement of braking (time of first pressing brake pedal).

For the condition of *night driving without headlights*, the general trend is very clear in Figure 6. Relative to the no $\Delta TTC_{virtual}$ manipulation events (0s), subjects pressed the brake pedal earlier on expansion events (0.2 and 0.4s) and thus were able to apply a smaller maximum force. Conversely, on contraction events (-0.2 and -0.4s) they pressed the brake pedal later, which compelled them to apply a larger maximum force. This suggests that braking earlier for the expansion events left a bigger margin of safety in terms of maximum braking force, that is, less emergency braking by the FD who now has extra time to respond. Alternatively, later braking had to be compensated for by harder braking, which is potentially more dangerous (for example due to loss of control caused by panic braking).

3.3. Maximum velocity difference

Since both subject controlled following vehicle (FV) and computer controlled leading vehicle (LV) were always driving at approximately the same speed (±3km/h) when the LV started its braking, the maximum velocity difference during braking is also an important index of braking behaviour, where ideally, were the two vehicles to decelerate in perfect synchrony, $V_{rel}=0$ throughout the braking event. In reality, if subjects braked sooner, the maximum velocity difference should be smaller and therefore the margin of safety larger. The converse should hold for later braking. These patterns are exactly what were observed in our data, shown in Figure 7.

For *maximum velocity difference*, a 3-way within-subjects ANOVA (viewing condition x manipulation x deceleration rate) indicated a significant viewing condition main effect ($F(2,118)=73.4$, $p<0.001$), a significant deceleration rate main effect ($F(2,118)=1939.2$, $p<0.001$), and a significant manipulation main effect ($F(4,116)=69.2$, $p<0.001$), with significant 2-way and 3-way interactions among viewing condition, deceleration rate and manipulation, except between viewing condition and deceleration rate. Three subsequent 2-way within-subject ANOVAs (manipulation x deceleration rate) were conducted for each viewing condition separately, revealing significant manipulation main effects for day condition ($F(4,116)=11.5$, $p<0.001$), night-time with headlights ($F(4,116)=32.2$, $p<0.001$) and without headlights ($F(4,116)=56$, $p<0.001$), with all significantly interacting with deceleration rate.

Three follow-up one-way within-subject ANOVAs (manipulation) were then conducted for each viewing condition for each deceleration rate. For *daytime*, a significant $\Delta TTC_{virtual}$

manipulation effect was found only for two deceleration rates, 6m/s^2 ($F(4,116)=5$, $p=0.001$) and 10 m/s^2 ($F(4,116)=12.2$, $p<0.001$), but not for 8 m/s^2. For *night driving with headlights* on the other hand, a significant $\Delta TTC_{virtual}$ manipulation effect was found for all deceleration rates: 6m/s^2 ($F(4,116)=3.9$, $p<0.005$), 8m/s^2 ($F(4,116)=13.5$, $p<0.001$) and 10m/s^2 ($F(4,116)=17.2$, $p<0.001$). Finally, for *night driving without headlights*, the three one-way within-subject ANOVAs (manipulation) also indicated a significant manipulation effects for all three deceleration rates (6m/s^2: $F(4,116)=5.5$, $p<0.001$; 8m/s^2: $F(4,116)=39.4$, $p<0.001$; and 10 m/s^2: $F(4,116)=41.3$, $p<0.001$).

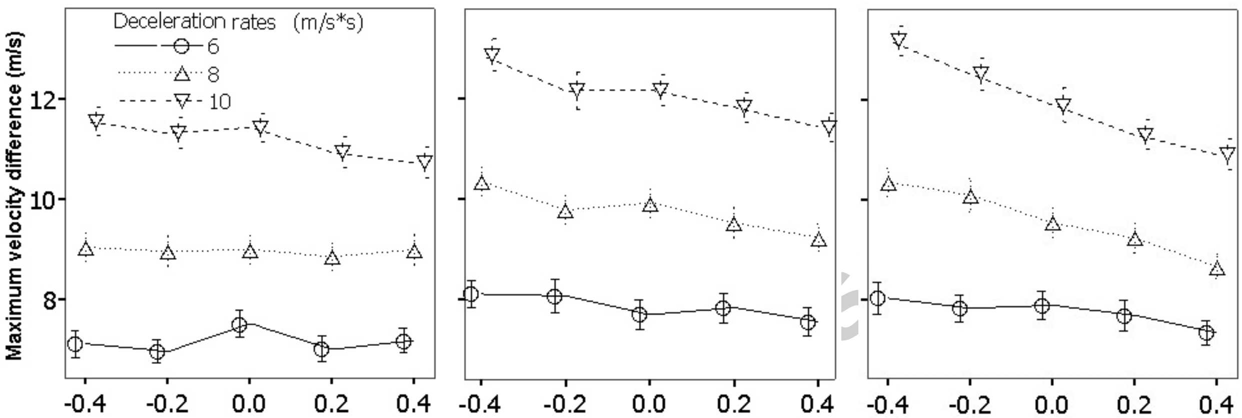


Figure 7. Maximum velocity difference (in m/s)

3.4. Minimum following distance

The final index of braking behaviour examined was the *minimum following distance* between the FV and the LV. This typically occurred when the FV started to reaccelerate at the end of a braking event, with a greater minimum following distance suggesting a larger safety margin. As shown in Figure 8, subjects in general achieved larger minimum following distances during braking on expansion events (0.2 and 0.4s) and shorter minimum following distances on contraction events (-0.2 and -0.4s) for night-time but not daytime conditions. A 3-way within-subjects ANOVA (viewing condition x manipulation x deceleration rate) indicated a significant viewing condition main effect ($F(2,118)=37.3$, $p<0.001$), a significant deceleration rate main effect ($F(2,118)=126$, $p<0.001$), and a significant manipulation main effect ($F(4,116)=34.6$, $p<0.001$) with a significant two-way and three-way interactions among viewing condition, deceleration rate and manipulation except between viewing condition and deceleration rate.

Three subsequent two-way within-subject ANOVAs (manipulation x deceleration rate) were conducted for each viewing condition separately, revealing significant manipulation main effects for day condition ($F(4,116)=6.3$, $p<0.001$), night-time with ($F(4,116)=19.3$, $p<0.001$) and without ($F(4,116)=26.3$, $p<0.001$) headlights conditions, with significantly interactions with deceleration rate only for day time and night time without headlights.

For daytime, three one-way within-subject ANOVAs (manipulation) for each deceleration rate showed a significant manipulation effect only for deceleration rates of 6m/s^2 ($F(4,116)=3.8$, $p=0.007$) and 10m/s^2 ($F(4,116)=16.1$, $p<0.001$). For night driving with headlights, a similar analysis showed a significant manipulation effect for all three deceleration rates: ($F(4,116)=4.1$, $p=0.004$) for 6 m/s^2, ($F(4,116)=7.3$, $p<0.001$) for8 m/s^2 and ($F(4,116)=12.4$, $p<0.001$) for 10m/s^2. For night driving without headlights, a significant manipulation effect was found only for deceleration rates of 8m/s^2 ($F(4,116)=23.6$, $p<0.001$) and 10 m/s^2 ($F(4,116)=31.2$, $p<0.001$), but not for 6 m/s^2.

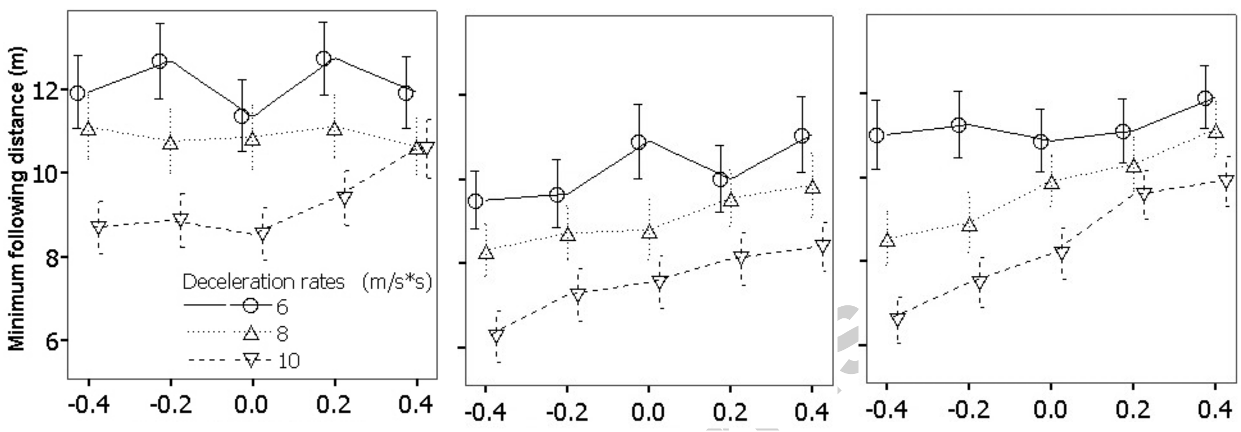


Figure 8. Minimum following distance (in m)

3.5. Minimum time-to-collision

The final overall performance parameter analysed was *minimum TTC*, which indicates the potential imminence of a collision. One advantage of this measure is that it provides a more global understanding of braking behaviour, since it integrates both distance and velocity information into one measure, and as such is potentially very valuable for directly reflecting any influence of $\Delta TTC_{virtual}$ manipulation without having to examine the individual gas and brake pedal measures. Clearly, the larger the TTC measure, the better the performance. As seen in Figure 9, subjects tended to achieve longer minimum TTC values during braking on expansion events (0.2 and 0.4s) and shorter TTC values on contraction events (-0.2 and -0.4s). A 3-way within-subjects ANOVA (viewing condition x manipulation x deceleration rate) indicated a significant viewing condition main effect ($F(2,118)=43$, $p<0.001$), a significant deceleration rate main effect ($F(2,118)=273.7$, $p<0.001$), and a significant $\Delta TTC_{virtual}$ manipulation main effect ($F(4,116)=31.4$, $p<0.001$), with a significant two-way and three-way interactions among viewing condition, deceleration rate and manipulation except between deceleration rate and manipulation.

Three subsequent 2-way within-subject ANOVAs (manipulation x deceleration rate) were conducted for each viewing condition separately, revealing significant manipulation main effects for the day condition ($F(4,116)=6.1$, $p<0.001$), night-time with ($F(4,116)=15.3$, $p<0.001$) and without ($F(4,116)=26.5$, $p<0.001$) headlights conditions, with significant interactions with deceleration rate only for day time and night time without headlights.

Nine one-way ANOVAs (manipulation) over 3 viewing conditions and 3 deceleration rates were performed. The results showed that the $\Delta TTC_{virtual}$ manipulation was significant only for daytime driving at deceleration rates of $6m/s^2$ ($F(4,116)=4.4$, $p=0.002$) and $10m/s^2$ ($F(4,116)=12.2$, $p<0.001$), night driving with headlights at deceleration rates of $6m/s^2$ ($F(4,116)=3.5$, $p=0.009$), $8m/s^2$ ($F(4,116)=9.4$, $p<0.001$) and $10m/s^2$ ($F(4,116)=11.7$, $p<0.001$), and night time driving without headlights at deceleration rates of only $8m/s^2$ ($F(4,116)=25.8$, $p<0.001$) and $10m/s^2$ ($F(4,116)=35.1$, $p<0.001$). We can also see that the greater the deceleration rate, the larger the effect of $\Delta TTC_{virtual}$ manipulation. This may be because imposed $\Delta TTC_{virtual}$ shifts have less of an influence on larger dependent TTC measures produced by slower deceleration rates during braking.

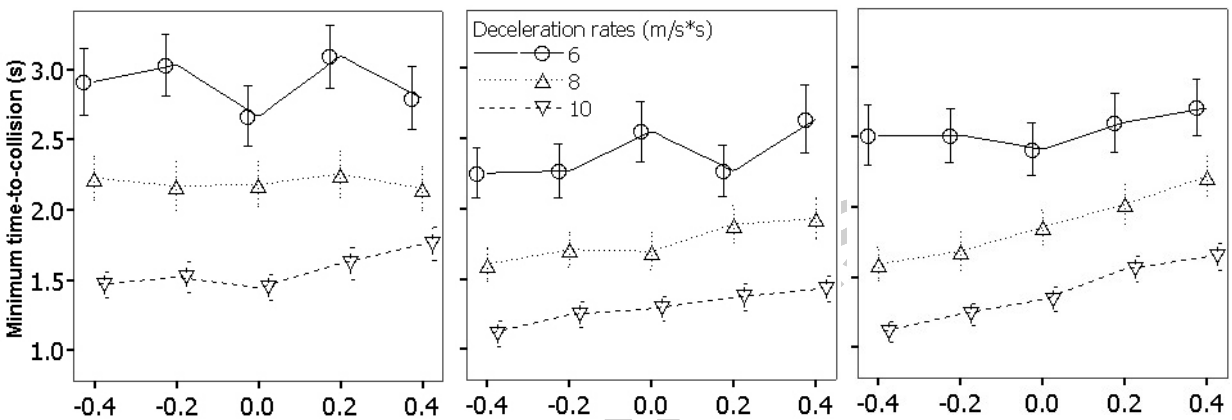


Figure 9. Minimum time-to-collision (TTC) (in seconds)

3.6. Questionnaire

At the end of experiment, subjects were asked, “In terms of the simulation of the automobile driving task, and within the obvious constraints of our driving simulator, did the lead vehicle image appear normal during the braking portion of the experiment?” All 40 subjects said it appeared normal to them. They were then further asked, “Actually, in this experiment we manipulated (by expanding or contracting) the separation and size of the image of the three brake lights on the lead vehicle during braking, but only for some of the braking events. Were you aware of this manipulation before reading this question?” 25 (62.5%) of the subjects said “Not at all”. 13 of them (32.5%) said “No, but I noticed something abnormal," with comments such as “When getting very close to the LV, sometimes I saw the brake lights moving apart or closer, but I thought it was a software glitch or was a normal way to simulate braking. I didn’t pay much attention to it”. Only 2 (5%) of the 40 participants answered “Yes,” with similar comments, but said that this didn’t change their braking behaviour; that is, they didn’t adopt any particular strategy to compensate for the unfamiliar cue available from the brake light image.

Another important introspective question concerned the strategies subjects used to maintain a proper following distance and respond to the braking events of the LV. The subjects indicated that they used the following cues: expansion of the size of the LV; expansion of the size of the rear window of the LV; rate of change of the distance between the LV and the FV; speed of the

LV passing the posts along the road; and speed of the LV passing the dashed centre lines. Although other cues existed in the driving simulator, and some subjects indicated that they had used them, the strong results from the dependent variables tested suggest that braking behaviour at night was dependent mainly on the relative expansion rate of the separation and size of the brake lights of the LV, which were manipulated in the experiment. Furthermore, the significant effect of $\Delta TTC_{virtual}$ manipulation was achieved in an apparently subconscious way, since even though we were not completely successful with our low fidelity simulator in programming the changes to be *imperceptible*, none of the subjects reported that they were aware of any manipulation of the size of the BLT having taken place during braking.

4. Discussion

The results reported here generally support our hypothesis: subjects braked sooner, to an extent corresponding to the magnitude of manipulation while viewing a LV whose brake lights are artificially expanding, at a rate compatible with its being closer to the LV in terms of effective virtual time shift ($\Delta TTC_{virtual}$). To complement this finding, subjects braked later while viewing a LV with brake lights artificially contracting, to an extent compatible with the magnitude of the contraction and at a rate compatible with being farther away from the LV. The greater effects occurred for the lower visibility conditions.

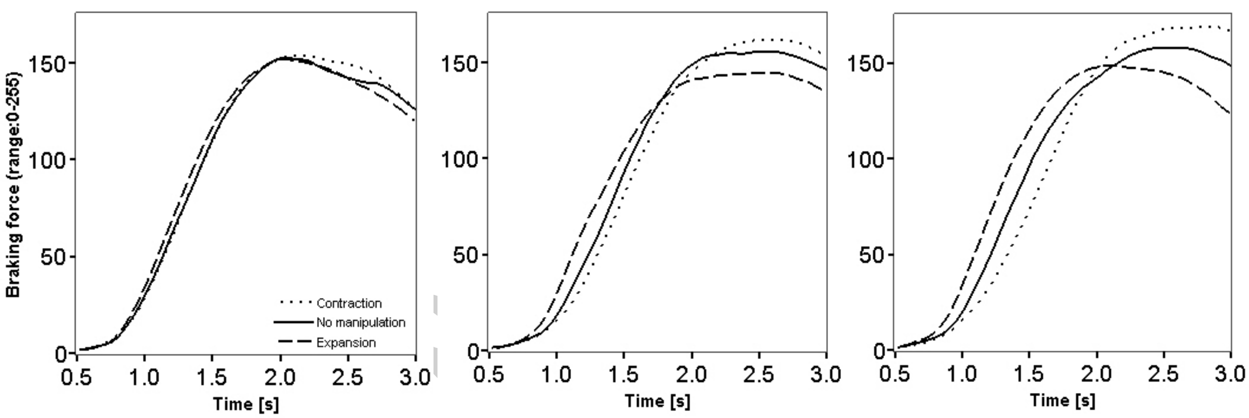


Figure 10. Averaged braking force profiles, starting 0.5 s after instant of braking, over three illumination conditions. Levels of $\Delta TTC_{virtual}$ manipulation (0.2s and 0.4s) and deceleration rates (6, 8, 10 m/s^2) have been collapsed into expansion (dashed line), no manipulation (solid line) and contraction (dotted line) events.

Figure 10 shows average braking force profile over three illumination conditions, daytime, night-time with FV headlights, and night time without FV headlights, with manipulation levels and deceleration rates lumped into three categories: $\Delta TTC_{virtual}$ expansion (comprising +0.2s and +0.4s), no $\Delta TTC_{virtual}$ manipulation (0s) and $\Delta TTC_{virtual}$ contraction (-0.2s and -0.4s). With respect to our prior theoretical hypothesis, the effect of the optical looming manipulation of the BLT was most clearly manifested during night-time driving. The pattern of the modified braking behaviour in Figure 10 is very clear: subjects generally brake earlier (and with less force) or later (and with more force) when exposed to a leave vehicle with, respectively, an expanding or contracting brake light triangle, relative to braking events with no size manipulation. Extending this finding to its practical implications, the concept of a dynamic brake light system shows some promise for causing drivers to brake sooner in emergencies mostly during night-time driving, especially along poorly illuminated roads, where drivers' ability to detect slowing traffic ahead tends to be diminished. Although the results are weaker, it is also possible that the same effect may be found to some degree during daytime driving, on the basis of our finding that, for the expansion direction, subjects braked earlier, and for the contraction direction, subjects brake harder relative to the no manipulation case.

Compared to one of our earlier experiments (Li & Milgram, 2005), in which the size of the entire leading vehicle was manipulated – a much more obvious cue than only brake lights – the effect of $\Delta TTC_{virtual}$ manipulation in this experiment is, not surprisingly, much smaller. As shown in Figure 11, our experiment showed that, for night driving with headlights, the start of braking was 50-125 ms sooner, and minimum TTC values during braking were up to 100-300 ms greater for the positive $\Delta TTC_{virtual}$ conditions. In particular, for $\Delta TTC_{virtual}$=+0.2s, the actual minimum TTC shift observed in the present experiment was approximately 0.15s, whereas it was about 0.3s in our earlier experiment. For $\Delta TTC_{virtual}$=0.4s, the corresponding values are approximately 0.25s and 0.55s respectively. Although these numbers may appear rather small, it is well known (Sivak & Flannagan, 1993) that reductions in brake reaction time of as little as 100ms (corresponding to 2.22 m at 80km/h) - a value achieved in the present experiment - can contribute in principle to a significant reduction in stopping distances during emergency braking in real life automobile driving, which could thus conceivably lead to significant reductions in both the frequency and severity of rear-end collisions.

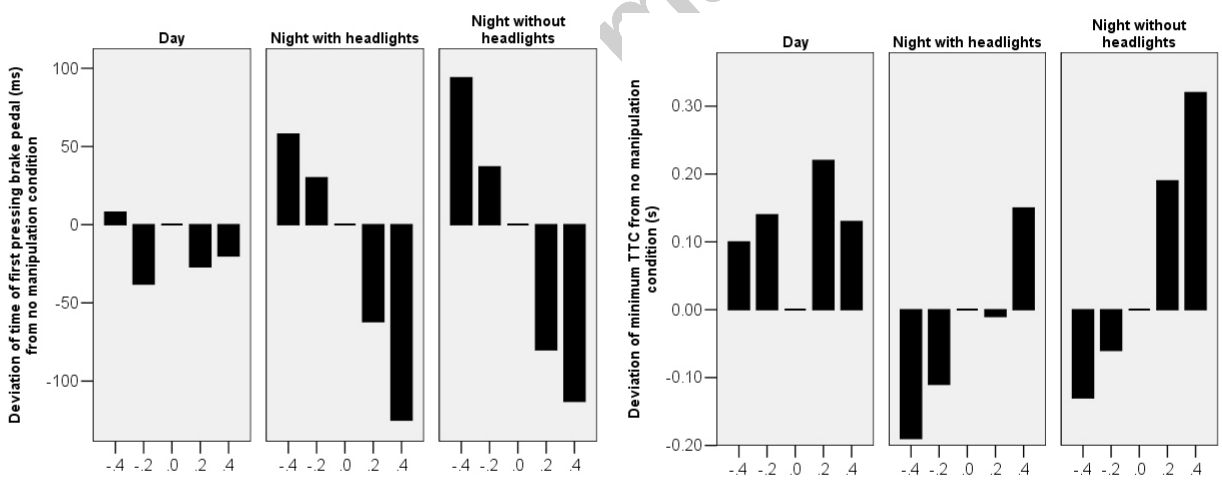


Figure 11. Deviation of time of first pressing brake pedal (in ms) (left) and deviation of average minimum TTC (in s) (right) for expansion events (+0.2s and +0.4s) and contraction events (-0.2s and -0.4s), relative to no manipulation events (0s) for daytime, night-time with, and night without FV headlights. Deceleration rates have been lumped into each manipulation condition. Positive or negative deviations for time of first braking represent later braking or earlier braking respectively. Positive and negative deviations for min TTC represent larger and smaller min TTC values respectively.

Another, somewhat surprising, finding from Figure 11 was that subjects achieved longer minimum TTC values in both contraction and expansion events compared to the no manipulation condition, for daytime driving. By reviewing Figure 5-9, we can see that this apparently occurred mostly for the 6m/s^2 deceleration rate (where subjects reacted later on no manipulation condition relative to all other manipulation conditions) and for the 10m/s^2 deceleration (where the manipulation effect was significant only for expansion). Although this finding doesn't conform to our theoretical expectation, its potential practical implication is that some kind of size manipulation, be it contacting or expanding, but especially expanding, apparently does influence drivers' braking behaviour. Furthermore the effect of such a change is in the favourable direction: to advance drivers' braking behaviour in emergencies.

As a final note on the practical implications of our investigation, on the one hand one could argue that the results reported here, which were obtained from a low fidelity, fixed base PC driving simulator, are unlikely to generalise to real-world driving conditions. It is nevertheless important to consider, however, that it might be more instructive to regard our investigation as lying primarily in the realm of applied visual perception research. That is, if it is possible, as we have shown, to selectively advance or retard subjects' response behaviour in a reliable manner, by manipulating one simple visual object distance cue – which is in fact imperceptible - within a low fidelity PC driving simulator, there is no reason to dismiss the possibility that similarly manipulating pertinent target objects during real world tasks such as automobile driving might similarly affect object distance perception. Needless to say, further research is needed to verify our findings and generalise them beyond the current low fidelity simulation.

If it proves effective, one could easily envisage the possibility of a dynamic brake light system implemented on real vehicles in the future, acting in a similar way to cause following drivers to react more quickly and brake more appropriately in emergency situations, thereby reducing the probability of a rear-end collision. With the help of on-board sensor technology to acquire data about vehicle following distances ($X_{rel}(t)$) and relative velocities ($V_{rel}(t)$), sufficient information would be available for implementing the dynamic brake light system. The size changes would have to be continuous during braking and compatible with the space available behind the (lead) vehicle, as prescribed through the explanation given here in Figure 3. It would also have to be scaled to be imperceptible for following drivers, in order to impose on them no extra conscious information processing. An equally important reason keeping the change imperceptible would be *not* to provide following drivers with the opportunity to compensate, by braking later rather than earlier because they have learned through experience to assume that they are being perceptually 'tricked'.

Although the dynamic brake light concept is not incompatible with other safety measures which involve enhancing conflict detection and avoidance by the following vehicle (FV), it is interesting to note that the proposed system follows a general self defence philosophy, in the sense that, in changing its own visual appearance (in a manner somewhat akin to members of the tetraodontidae or blowfish family), more of the responsibility for collision avoidance would be given to the lead vehicle, which stands to suffer more severe consequences during a rear end collision. One of the potentially most attractive aspects of the concept, furthermore, is the fact that no authority would be removed from the following driver, who would remain completely within the control loop, in contrast to other automated safety measures which might be programmed to take over control of the FV during emergencies.

Finally, it should also be noted that the kind of size manipulation described here would be activated only during rapid braking of the LV, since current brake lights are arguably quite sufficient for slow and moderate braking. Another reason for limiting manipulation to rapid braking would be to avoid FD habituation and thus ensure effectiveness during actual hard braking, when it is most needed. In conclusion, therefore, our objective is that this research will potentially contribute to further reductions in rear-end collisions, in a manner analogous to the introduction of the well known centre high mounted brake light. That arguably revolutionary safety system, which is to be found in all modern automobiles, is reported to have reduced reaction times by *0.11 seconds* for passenger car drivers, a result which translated into a 8.5% reduction during the early years of its introduction and a subsequently stable 4-5% reduction in rear impact crashes (Kahane and Hertz, 1998; Farmer, 1996).

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Glossary of Abbreviations and Symbols

BLT:	Brake Light Triangle
FD:	Following Driver
FV:	Following Vehicle
LD:	Lead Driver
LV:	Lead Vehicle
R(t):	Graphical scaling factor
TTC:	Time To Collision
$\Delta TTC_{virtual}$	Effective Virtual Time Shift
$V_{rel}(t)$:	Velocity of FD Relative to LV
$X_{rel}(t)$:	Instantaneous Distance between the FD's Viewpoint and the Rear of the LV
$X_{virtual}(t)$	Effective Offset Distance