Accident Analysis and Prevention 118 (2018) 114–124

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Using perceptual cues for brake response to a lead vehicle: Comparing threshold and accumulator models of visual looming

Qingwan Xue[a], Gustav Markkula[b], Xuedong Yan[a,*], Natasha Merat[b]

[a] MOE Key Laboratory for Urban Transportation Complex System Theory and Technology, School of Traffic and Transportation, Beijing Jiaotong University, Beijing, 100044, PR China

[b] Institute for Transport Studies, University of Leeds, Leeds, LS2 9JT, United Kingdom

ARTICLE INFO

Keywords:
Rear-end collision
Brake response time
Multilevel model
Visual looming
Threshold model
Accumulator model

ABSTRACT

Previous studies have shown the effect of a lead vehicle's speed, deceleration rate and headway distance on drivers' brake response times. However, how drivers perceive this information and use it to determine when to apply braking is still not quite clear. To better understand the underlying mechanisms, a driving simulator experiment was performed where each participant experienced nine deceleration scenarios. Previously reported effects of the lead vehicle's speed, deceleration rate and headway distance on brake response time were firstly verified in this paper, using a multilevel model. Then, as an alternative to measures of speed, deceleration rate and distance, two visual looming-based metrics (angular expansion rate $\dot{\theta}$ of the lead vehicle on the driver's retina, and inverse tau τ^{-1}, the ratio between $\dot{\theta}$ and the optical size θ), considered to be more in line with typical human psycho-perceptual responses, were adopted to quantify situation urgency. These metrics were used in two previously proposed mechanistic models predicting brake onset: either when looming surpasses a threshold, or when the accumulated evidence (looming and other cues) reaches a threshold. Results showed that the looming threshold model did not capture the distribution of brake response time. However, regardless of looming metric, the accumulator models fitted the distribution of brake response times better than the pure threshold models. Accumulator models, including brake lights, provided a better model fit than looming-only versions. For all versions of the mechanistic models, models using τ^{-1} as the measure of looming fitted better than those using $\dot{\theta}$, indicating that the visual cues drivers used during rear-end collision avoidance may be more close to τ^{-1}.

1. Introduction

According to statistics provided by the World Health Organization, about 1.25 million people die each year as a result of road traffic crashes (WHO, 2015). Among all the collisions types, rear-end crashes account for about 20% of all crashes in Shanghai, China (Wang et al., 2016) and 32% approximately in the US (National Highway Traffic Safety Administration, 2014).

To avoid rear-end collisions, the initiation of a brake response, when required, is of great importance. Total brake response time is defined as the time from stimulus appearance to the reaction of the driver, plus the movement time to hit the brake pedal (Schweitzer et al., 1995). It is a measurement which has been widely used and analysed in crash-related investigations. Previous studies have reported that brake response time values vary in a large range under different conditions (Johansson and Rumar, 1997; Sohn and Stepleman, 1998; Green, 2000). Summala (2000) suggested that urgency of a situation was one of the factors which may affect drivers' brake response time. Situation urgency can be described by the behaviour of the lead vehicle (e.g. lead vehicle's deceleration rate) and the driving state when the lead vehicle's brake onset (e.g. headway distance and time to collision). Liebermann et al (1995), Schweitzer et al. (1995) and Summala et al. (1998) tested the effects of speed and following distance on reaction time, finding that drivers reacted faster at a shorter following distance, whereas the driving speed did not show any significant effects both in Liebermann et al (1995) and Schweitzer et al. (1995) studies. Hulst et al., 1999 tested the effects of a lead vehicle's deceleration rate on response time, and showed that this was longer for slow deceleration rates. The combined effect of a lead vehicle's deceleration rate and driving distance on response time has also been studied by Lee et al. (2002) and Wang et al. (2016), who showed that drivers responded faster when the lead vehicle's deceleration increased or when the initial headway decreased. Li et al (2016) tested the effect of driving speed, headway distance, gender and cell phone use on drivers' brake response time and showed that drivers reacted faster with faster speed and reduced headway distance. Therefore, although the overall behavioural pattern

* Corresponding author.
E-mail addresses: 14114258@bjtu.edu.cn (Q. Xue), g.markkula@leeds.ac.uk (G. Markkula), xdyan@bjtu.edu.cn (X. Yan), n.merat@its.leeds.ac.uk (N. Merat).

https://doi.org/10.1016/j.aap.2018.06.006
Received 15 March 2018; Received in revised form 27 May 2018; Accepted 11 June 2018
0001-4575/

emerging from previous studies suggest that brake response time decreases with increasing situation urgency, the effect of a lead vehicle's speed, lead vehicle deceleration, and initial headway to the lead vehicle, on drivers' brake response times has not yet been considered. Thus, the first goal of this paper was to test the overall effect of the above mentioned variables on drivers' brake response time.

According to previous studies, during a rear-end collision avoidance process, drivers control braking on the basis of their assessment of the situation urgency. However, the extent to which drivers can perceive the lead vehicle's distance, speed and deceleration information is not clear. Since brake lights do not indicate how hard the lead vehicle is braking, drivers have to rely on other visual information to determine how rapidly they are closing in on the lead vehicle (Lee, 1976). One much-studied form of such information is *visual looming*, which is produced by an object moving towards the subject, and may indicate an impending collision (Terry et al., 2008). The angular projection of an object on the subject's retina is defined as θ, with $\dot{\theta}$ being the angular expansion rate (Lee, 1976). Liebermann et al. (1995) pointed out that changes in angular velocity during optical expansion of the lead vehicle may be used as a cue to modulate braking movement, and Yilmaz and Warren (1995) provided empirical support for this idea.

Previous authors have often assumed that there is a threshold at which drivers realize that they are approaching the lead vehicle in such a way that they must take some action to avoid a rear-end collision (Lamble et al., 1999; Muttart, 2005; Olson et al., 2010; Maddox and Kiefer, 2012). One version of this threshold, which has often been discussed in the literature, is looming *detection* threshold, which is the minimum threshold at which drivers start perceiving the threat, and is generally assessed using $\dot{\theta}$. These threshold models assume that drivers respond within 0.75–2 s after reaching the detection threshold (Plotkin, 1976; Mortimer, 1990). Maddox and Kiefer (2012) assumed three candidate values of perception-reaction time, and examined real-world accident data to obtain an estimate of the detection threshold, but found that the data could be described by a range of possible combinations of detection thresholds and reaction times. Another type of threshold model just assumes a single *response* threshold, at which drivers start directly responding to the threat. There have been a number of studies investigating response threshold models (Lee, 1976; Kiefer et al., 2003; Flach et al., 2004) but all assuming slightly different looming cues. Lee (1976) suggested that braking performance might be contingent on the optical parameter τ and its derivative $\dot{\tau}$. τ is the ratio of θ and $\dot{\theta}$. τ has units of time and is an approximation of time-to-contact. Drivers are assumed to start their braking actions when τ reaches a certain margin value τ_m. The inverse of τ, τ^{-1} has also been considered as a cue in near-accident control. Kiefer et al. (2003) developed a model which is based on a τ^{-1} threshold that decreases linearly with own driving speed. Kondoh et al. (2014) demonstrated the tight connection between drivers' perception of risk and τ^{-1}, following a driving simulator experiment.

However, it seems reasonable to assume that in real traffic, drivers' response behaviour is not only based on responding to perceptual quantities such as τ^{-1}. The stimulus in the threshold models mentioned above has been limited to visual looming, while various other stimuli were ignored (e.g., brake light onset). An alternative to the threshold model, which has been proposed by Markkula and colleagues (Markkula, 2014; Markkula et al., 2016) is the *accumulator* model, suggesting that visual looming might be used as *one* source of evidence for the need to brake, combined with other sources of evidence in noisy accumulation (i.e., integration), to a decision threshold at which brake onset occurs. Markkula et al. (2016) showed that qualitative patterns of brake timing in naturalistic near-crashes and crashes aligned better with this type of account than with a threshold-based account.

Accumulator-type models have been studied extensively in perceptual decision tasks in the laboratory, often using Ratcliff's (1978) drift diffusion model. The underlying assumption is that the brain extracts, per time unit, a piece of evidence from the stimulus (drift) which is disturbed by noise (diffusion) and subsequently accumulates these over time, until a decision criterion is hit, at which point a response is initiated (Ratcliff and Smith, 2004; Ratcliff and Strayer, 2011; Bitzer et al., 2014). These models have been applied in a variety of domains such as psychology and neuroscience (Gold and Shadlen, 2001; Ratcliff et al., 2003; Schall et al., 2011; Roe et al., 2001; Krajbich and Rangel, 2011). Ratcliff and Strayer (2014), successfully fitted this type of model to a distribution of reaction times to the lead vehicle's brake lights, in a simulated driving task, but did not consider the possible influence of situation urgency, e.g., in terms of visual looming on response.

Although the role of visual looming in driver brake action has been investigated in previous studies, the threshold and accumulator types of model have not been stringently compared, and especially not in their ability to model *distributions* of brake response times. Therefore, both types of model, referred to here as *mechanistic* models (since they propose specific mechanisms for what determines brake onset), were tested here, with the aim of investigating which of the two hypothesised mechanisms better explains human brake timing distributions. For different versions of the visual looming-based mechanistic models, perceptual cues were quantified both as $\dot{\theta}$ and τ^{-1}; the comparison of these two cues was another aim of this study. Finally, as the multilevel model is a linear model, based on values such as speed, deceleration and distance. A comparison between multilevel model fitting and accumulator model fitting was conducted, to see whether the accumulator model can be an alternative to the regression analysis, when considering the effects of scenario urgency on drivers' response time.

2. Methodology

2.1. Equipment

The equipment used in this experiment was the Beijing Jiaotong University driving simulator (as shown in Fig. 1). The simulator was produced by Real-time Technologies. Inc in U.S. It is composed of a cabin of a Ford Focus with automatic gearbox, gas/brake pedal and other components, which are in full accordance with the real vehicle.

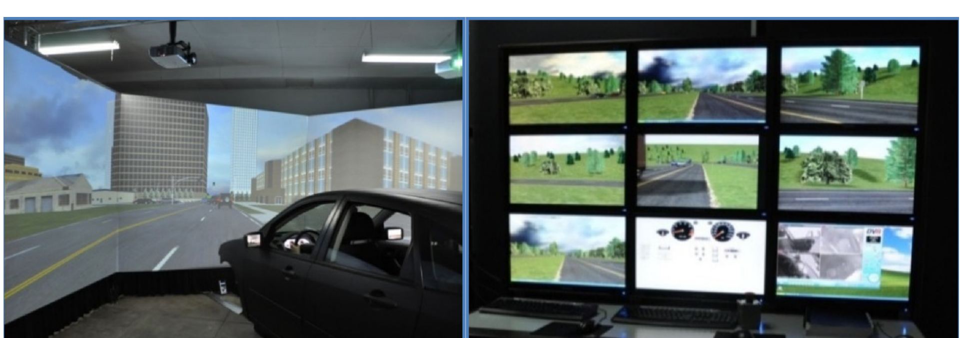

Fig. 1. Illustration of the driving simulator system.