Accident Analysis and Prevention 95 (2016) 209–226

Contents lists available at ScienceDirect

Accident Analysis and Prevention

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

A farewell to brake reaction times? Kinematics-dependent brake response in naturalistic rear-end emergencies

Gustav Markkula[a,b,*], Johan Engström[a,c], Johan Lodin[a], Jonas Bärgman[c], Trent Victor[c,d]

[a] Volvo Group Trucks Technology, Advanced Technology and Research, M1.6, 405 08 Göteborg, Sweden
[b] Institute for Transport Studies, University of Leeds, LS2 9JT, Leeds, United Kingdom
[c] Department of Applied Mechanics, Chalmers University of Technology, 419 96 Göteborg, Sweden
[d] Volvo Cars Safety Centre, 418 78 Göteborg, Sweden

ARTICLE INFO

Article history:
Received 1 March 2016
Received in revised form 23 June 2016
Accepted 7 July 2016

Keywords:
Rear-end crashes
Reaction time
Kinematics
Visual looming
Deceleration

ABSTRACT

Driver braking behavior was analyzed using time-series recordings from naturalistic rear-end conflicts (116 crashes and 241 near-crashes), including events with and without visual distraction among drivers of cars, heavy trucks, and buses. A simple piecewise linear model could be successfully fitted, per event, to the observed driver decelerations, allowing a detailed elucidation of when drivers initiated braking and how they controlled it. Most notably, it was found that, across vehicle types, driver braking behavior was strongly dependent on the urgency of the given rear-end scenario's kinematics, quantified in terms of visual looming of the lead vehicle on the driver's retina. In contrast with previous suggestions of brake reaction times (BRTs) of 1.5 s or more after onset of an unexpected hazard (e.g., brake light onset), it was found here that braking could be described as typically starting less than a second after the kinematic urgency reached certain threshold levels, with even faster reactions at higher urgencies. The rate at which drivers then increased their deceleration (towards a maximum) was also highly dependent on urgency. Probability distributions are provided that quantitatively capture these various patterns of kinematics-dependent behavioral response. Possible underlying mechanisms are suggested, including looming response thresholds and neural evidence accumulation. These accounts argue that a naturalistic braking response should not be thought of as a slow reaction to some single, researcher-defined "hazard onset", but instead as a relatively fast response to the visual looming cues that build up later on in the evolving traffic scenario.

1. Introduction

When the driver of a vehicle is suddenly faced with an unexpected, critical risk of collision, how does he or she respond? If evasive maneuvering is applied, when does it begin? How is it carried out?

Conclusive answers to these questions have been a long-standing objective of traffic safety research, and have a range of implications: In the design of roads, vehicles, or vehicle support systems for safety and automation, quantitative models of driver behavior can be very directly applied, for example in system algorithms or in computer simulations of crashes (e.g., Perel, 1982; Fambro et al., 2000a; MacAdam, 2001; Brännström et al., 2010; Markkula, 2015). In the broader study of traffic safety, the way one thinks about drivers' emergency responses can also be important in more subtle ways, for example by shaping design of experiments and subsequent interpretations of results, or by guiding one's analysis of actual crashes to understand their causation (e.g., Naing et al., 2009; Engström et al., 2013b), sometimes for purposes of litigation (e.g., Maddox and Kiefer, 2012).

The driver's *reaction time* (RT) is a concept that traffic safety researchers have repeatedly made use of in models, when designing studies, and when analyzing driver behavior close to crashes. The RT usually represents the time duration from the appearance of a potential hazard, such as a lead vehicle's brake lights activating, until the driver under study initiates some form of evasive response (Society of Automotive Engineers, 2015). Especially for braking responses, there is a considerable literature measuring *brake reaction times* (BRTs) and how they are influenced by factors such as driver age, gender, cognitive load, situation urgency, number of stimuli for the driver to consider, warnings, and so on (see for example the studies by Barrett et al., 1968; Olson and Sivak, 1986; Fambro et al., 1998; McGehee et al., 1999; Lee et al., 2002; Jurecki

* Corresponding author. Markkula was with Volvo Group Trucks Technology during most of the work reported here, but is now at Institute for Transport Studies, University of Leeds, LS2 9JT, Leeds, United Kingdom.
E-mail address: g.markkula@leeds.ac.uk (G. Markkula).

http://dx.doi.org/10.1016/j.aap.2016.07.007
0001-4575/

and Stańczyk, 2009, 2014; Fitch et al., 2010; Ljung Aust et al., 2013; and the reviews by Olson, 1989; Green, 2000; Muttart, 2003, 2005).

Green's much-cited review (2000) aimed to determine typical RT values for different driving conditions. *Expectancy* was identified as the major factor determining BRT, with estimated values of 0.70–0.75 s for fully anticipated events, 1.25 s for unexpected but common events such as brake light onsets, and 1.5 s for surprise events such as sudden path intrusions. These canonical, situation-independent, BRT values drew criticism from Summala (2000), who pointed to evidence that BRTs for highly unexpected events can, if the traffic scenarios in question are sufficiently urgent, decrease to 1 s or lower. Similar dependencies between situation *kinematics* (the relative motion of involved road users, in terms of distances, speeds, etc.) and BRT have been reviewed by Muttart (2003, 2005) and have also been demonstrated in more recent test track and driving simulator studies (Jurecki and Stańczyk, 2009, 2014; Engström, 2010; Ljung Aust et al., 2013). However, a detailed, large-scale analysis is still outstanding, especially for naturalistic (i.e. real-traffic) emergencies.

As for what happens beyond the point of brake onset, it has been reported from both controlled and naturalistic studies that drivers will often, but not always, show maximum deceleration levels close to their vehicle's limits on the given road (McGehee et al., 1999; Fambro et al., 2000b; Lee et al., 2007). From some controlled studies, there are also reports of progressive or step-wise ramping up towards these maximum levels (Prynne and Martin, 1995; Fambro et al., 2000b; Lee et al., 2002). Again, a detailed, quantitative account of emergency braking control is lacking, especially for naturalistic data.

This paper presents time-series analyses of situation kinematics and driver braking behavior observed in naturalistic rear-end crashes and near-crashes, continuing from the work by Victor et al. (2015, pp. 76–84). They showed, for one set of naturalistic passenger car data, that when visually distracted drivers looked back to the road to find a rear-end collision threat, the time delay before they exhibited any discernible *physical reaction* to the situation was strongly kinematics-dependent. Here, these results are extended by including (1) not only driver physical reaction but also actual measured deceleration behavior, (2) events without any off-road eye glances, and (3) an additional data set of recorded events that includes truck and bus drivers in addition to car drivers.

It will be described here how drivers' deceleration behavior in the studied events varied markedly with situation kinematics, in certain rather specific manners, across data sets and vehicle types. Statistical-level descriptions of this variability, potentially useful in quantitative approaches to traffic safety, will be provided. Possible psychological mechanisms behind the observed behaviors will be discussed, and it will also be argued that the findings make the concept of a "brake reaction time" seem inadequate as a means for describing and understanding driver behavior in surprise emergencies.

2. Method

2.1. Data sets

The naturalistic events analyzed here came from two different sources: passenger car events from the Second Strategic Highway Research Program (SHRP 2), and passenger car, heavy truck, and bus events from the Analysis of Naturalistic External Datasets (ANNEXT) project. Table 1 provides an overview of the number of events per data set and vehicle type. In the remainder of this paper, the truck and bus events will be combined and treated together.

Table 1
Number of naturalistic rear-end events by data set and subject vehicle type.

	SHRP 2	ANNEXT			
	Passenger car	Passenger car	Heavy truck	Bus	Total
Crashes	46	26	28	16	116
Near-crashes	211	11	11	8	241

Within SHRP 2, the world's largest naturalistic driving study to date was carried out, collecting over 80 million kilometers of driving data from instrumented cars driven by 3147 drivers across six sites in the US. As noted above, the present paper describes analyses building on those by Victor et al. (2015), comprising 46 crashes and 211 near-crashes; more specifically all of the critical events in the SHRP 2 database that were categorized as being of rear-end type (Scenarios 22–26 in the taxonomy by Najm et al., 2007) at the time of data extraction (spring of 2014).

ANNEXT was a pilot project between Lytx, Chalmers University of Technology and AB Volvo, which selected and annotated naturalistic crashes and near-crashes, originally recorded by Lytx as part of a behavior-based safety program for commercial fleets. The present paper uses the 100 rear-end events collected by the ANNEXT project; 77 events from the US and 23 events from Africa (South Africa, Nigeria, Zambia, and Zimbabwe). These events were selected using the following criteria: (1) The speed of the subject vehicle should be higher than 15 km/h at the start of the evasive maneuver or the moment of crash impact (thus excluding minor low-speed crashes), (2) the driver of the subject vehicle should not be wearing sunglasses, and (3) the lead vehicle should remain in the same lane from the beginning of the event until the crash (thus excluding cut-in events).

For both SHRP 2 and ANNEXT, candidate events were identified using various triggers, such as acceleration thresholds. In SHRP 2, candidate events were also identified by Automatic Crash Notification algorithms running in the vehicles, incident button presses by the participating drivers, and reports by the organizations that performed the data collection. In both projects, human video reviewers made the final judgment on whether the captured event was a true crash ("any contact [. . .] with an object [. . .] at any speed in which kinetic energy is measurably transferred or dissipated"; Victor et al., 2015), a near-crash ("any circumstance that requires a rapid, evasive maneuver [. . .] that approaches the limits of the vehicle capabilities. As a general guideline, subject vehicle braking greater than 0.5 g or steering input that results in a lateral acceleration greater than 0.4 g to avoid a crash constitutes a rapid maneuver"; ibid.), or neither.

For further details on the SHRP 2 and ANNEXT data sets, including driver demographics and other descriptive variables, see (Victor et al., 2015) and (Engström et al., 2013b).

The data variables used in the present analyses were:

- Manually annotated time point of first discernible *physical reaction* of the subject vehicle's driver to the collision threat ("including body movement, posture, a change in facial expression, a movement of the leg toward the brake", Victor et al., 2015; see also McGehee and Carsten, 2010; for further insight into these types of physical reactions to critical traffic events).
- Manually annotated time-series of the *eye glance behavior* of the subject vehicle's driver, detailing whether gaze was directed toward the road ahead or not (using the "Eyes on Path" definition on p. 26 of Victor et al., 2015), as well as whether eyes were closed or open. For the SHRP 2 dataset these annotations were made by two annotators separately to increase reliability; see (Klauer et al., 2010) for more details on the adopted procedure.
- Manual annotation of the *evasive maneuver* applied by the subject vehicle's driver, here reduced to the following categories: braking; steering; braking and steering; no maneuver.