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A test-based method for the assessment of pre-crash warning and braking systems

András Bálint[a,*], Helen Fagerlind[a], Anders Kullgren[a,b]

[a] Division of Vehicle Safety, Department of Applied Mechanics, Chalmers University of Technology, SE-41296 Gothenburg, Sweden
[b] Folksam Insurance, Bohusgatan 14, SE-10660 Stockholm, Sweden

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ABSTRACT

In this paper, a test-based assessment method for pre-crash warning and braking systems is presented where the effectiveness of a system is measured by its ability to reduce the number of injuries of a given type or severity in car-to-car rear-end collisions. Injuries with whiplash symptoms lasting longer than 1 month and MAIS2+ injuries in both vehicles involved in the crash are considered in the assessment. The injury reduction resulting from the impact speed reduction due to a pre-crash system is estimated using a method which has its roots in the dose–response model. Human–machine interaction is also taken into account in the assessment. The results reflect the self-protection as well as the partner-protection performance of a pre-crash system in the striking vehicle in rear-end collisions and enable a comparison between two or more systems. It is also shown how the method may be used to assess the importance of warning as part of a pre-crash system.

1. Introduction

Forward-looking crash avoidance and mitigation systems are safety systems that scan the road in front of the equipped vehicle (typically by use of radars or cameras), detect other vehicles and/or pedestrians and trigger various mechanisms such as warning, brake enforcement or autonomous emergency braking when certain pre-programmed criteria are met. As a result of these actions, the speed of a vehicle equipped with the system is decreased with or without driver interference, and thereby a crash may be avoided or else the forces that are present in the impact are mitigated and consequently the severity of injuries could be decreased. This paper is focused on the assessment of systems that use warning and/or autonomous emergency braking; these systems will henceforth be referred to as *pre-crash warning and braking systems* (*PCWBS*).

A large variety of PCWBS is already available on the market; for a comprehensive list, see Atalar et al. (2012). There are large differences in the functionality of systems by different manufacturers. The safety benefits of manufacturer-specific as well as generic PCWBS have been quantified in a number of studies, see Isaksson-Hellman and Lindman (2012), Ressle et al. (2011), Kusano and Gabler (2011) and the references therein for recent examples.

PCWBS with vehicle detection (as opposed to pedestrian detection) may have a safety benefit in rear-end collisions, which are crashes where the front of one vehicle (called *subject vehicle*) impacts the rear of another vehicle (called *target vehicle* or *lead vehicle*) travelling in the same direction. These are frequently occurring crash types with potentially long-term injury consequences and are linked to human suffering and high costs for society (see Najm et al., 2003). Recently, ranking of crash scenarios in the ASSESS project (McCarthy et al., 2009; Wisch et al., 2010) has shown high relevance of rear-end collisions in terms of their frequency and the societal cost of injuries sustained in this crash type. These results underline the importance of the development and the assessment of safety systems that have a potential to decrease the number or the severity of rear-end crashes.

Most studies on PCWBS consider the effect of safety systems on injuries defined in terms of a maximum Abbreviated Injury Scale value (MAIS, see Gennarelli and Wodzin, 2005). In particular, it is common to consider MAIS2+ injuries, which have a maximum AIS level of 2 or higher, including fatal injuries. However, besides serious and fatal injuries, a major problem related to rear-end crashes is the prevalence of *whiplash injuries*, or more precisely, injuries with whiplash symptoms (Richter et al., 2000; NHTSA, 2004; Kullgren et al., 2007). These are injuries of the neck that may cause various short-term or long-term symptoms (such as pain in the neck or shoulders, headache, dizziness, *etc.*) and have large economical costs. A whiplash injury is defined here as *long-term* if symptoms last longer than 1 month.

Whiplash injuries, even those with long-term symptoms, are assigned AIS level of 1 hence long-term whiplash injuries and MAIS2+ injuries together cover most injuries occurring in rear-end

* Corresponding author. Tel.: +46 31 772 3648.
E-mail address: andras.balint@chalmers.se (A. Bálint).

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crashes (the only injuries that are not covered here are injuries with maximal AIS level 1 without whiplash symptoms lasting longer than 1 month after the crash). This combination of injuries (together with other injury levels) was studied in Kullgren (2008), using the *dose–response model* as the main tool in the assessment. This stochastic model estimates the number of injured occupants (*i.e.*, the response) from the injury risk and crash frequency (*i.e.*, the dose) functions (see Kullgren, 2008 and Korner, 1989). The assessment method that will be described in the present paper has its roots in the dose–response model hence it is important to understand its input functions.

An injury risk function describes a statistical relationship between a crash severity parameter and the risk of sustaining a certain injury based on a particular sample of crashes. In reality, the individual injury risk is influenced by a multitude of factors (occupant age, occupant biometrics, vehicle age and passive safety performance of the vehicle, *etc.*), but an approximation for the whole population can be made by selecting an average relationship which takes only one variable into account, which is most commonly chosen to be Delta-V (see Gabauer and Gabler, 2008; Dischinger et al., 1998; Roberts and Compton, 1993).

The other input of the dose–response model is crash frequency, which describes the number (alternatively, the percentage) of crashes at all values of the crash severity parameter. The underlying parameter must be the same as that for the injury risk function; *i.e.*, if the latter function is defined in terms of Delta-V, then it can only be paired with a crash frequency function that gives the number of crashes at different values of Delta-V.

Once the two dose functions are determined, it is immediate to obtain the number of injured occupants at any interval of Delta-V using the dose–response model. Consequently, if it is known how the dose functions are transformed by a safety system, then the dose–response model allows a comparison of the number of injured occupants with and without the system (even for any given interval of Delta-V).

However, the transformed functions are very rarely known but rather they have to be estimated. Autonomous braking is often assumed to shift the crash frequency function towards smaller values of Delta-V by a given amount (Kullgren, 2008). Alternatively, crash frequency may be modelled by lognormal distribution (which, as pointed out in Kononen et al. (2010), is a reasonable approximation, see Section 2.4) and the parameters of the distribution may be adjusted on the logarithmic level to model the effect of the safety system (Flannagan, C., personal communication). This paper uses a new approach in which the expected crash frequency of the vehicle equipped with the safety system is estimated by crash testing.

The aim with the present paper is to develop a test-based system assessment of PCWBS in car-to-car rear-end collisions which reflects the reduction due to the safety system in the number of occupants (in both vehicles) sustaining MAIS2+ and whiplash injuries. It is required that the method is directly implementable in practice and allows presentation of the results to a wide audience.

In Section 2, the background data of the assessment method is discussed, together with the specification of the test protocol that is used in the assessment procedure. Section 3 contains details on the weighting of different tests and the mathematical formulas by which the injury reduction is estimated from the test results. It is demonstrated in Section 3.4 how the assessment procedure could be modified to evaluate the usefulness of the warning component in a pre-crash system. Finally, a brief discussion on the assessment method and its limitations is provided in Section 4.

2. Materials and methods

This section describes the background data necessary for the method which will be described thoroughly in Section 3. In particular, the test scenarios that the method is applied on are specified in Section 2.2. The dose functions used in the assessment are described in Sections 2.3 and 2.4. However, first the definitions of two important concepts whose understanding is essential for the rest of the paper are given in Section 2.1.

2.1. Relative impact speed versus Delta-V

This section contains the definitions of relative impact speed and Delta-V and a simplifying assumption relating these concepts to each other which is used throughout this paper.

- *Relative impact speed* is the speed difference between the subject vehicle and the target vehicle *immediately before the crash*.
- *Delta-V* (of the subject vehicle) is the change of velocity of the subject vehicle *due to the crash* (*i.e.*, the difference between the velocity at impact and the residual velocity after energy absorption and interaction with the target vehicle).

Delta-V defines the change in vehicle velocity associated with primary force of the impact. It depends on the relative impact speed, the respective masses of the vehicles and the coefficient of restitution. Delta-V is often used as a predictor of injury because it includes the weight characteristics in addition to the speeds and directions of the vehicles involved. Therefore, the injury reduction due to a pre-crash system could be estimated using a comparison of Delta-V measured in a test without (the activation of) the system and that in a test with the system with the understanding that Delta-V is zero if the crash is avoided.

However, testing without the pre-crash system would entail unnecessary costs hence instead of actually performing the tests it would be preferable to compute Delta-V without the system from the initial conditions of the tests. One way to do this is to compute what the relative impact speed would be without a system and relate this to Delta-V using certain rules based on physical considerations.

In this paper, *Delta-V is approximated as half the relative impact speed in the test*. This approximation is valid in certain rear-end crashes (such as the case of 100% overlap, equal mass of vehicles and no restitution in the impact) and this relationship between Delta-V and relative impact speed may be the best linear approximation available for generic rear-end crashes. In Section 2.2 it will be described for every test scenario how the relative impact speed without the system is derived from the initial conditions of the test.

2.2. Test scenarios

Based on the frequency and injury severity of real-world rear-end crashes, three sub-scenarios (see below) within rear-end collisions are considered. It is important that the test scenarios cover the whole speed range that is relevant to rear-end collisions, which is ensured by an incremental initial test speed approach in Scenarios 1–2 and varied braking and headway conditions in Scenario 3. The initial test speed of the subject vehicle will be denoted by $V_{initial}$.

Scenario 1: Stopped lead vehicle. In this scenario, $V_{initial}$ varies between 10 km/h and 80 km/h using 5 km/h increments while the target vehicle is standing still at a given distance in front of the subject vehicle. The relative impact speed without a PCWBS is $V_{initial}$.

Scenario 2: Slower lead vehicle. The subject vehicle has initial speeds between 50 km/h and 80 km/h, again using 5 km/h increments, while the target vehicle has a constant speed of 20 km/h. In