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Impact characteristics of a vehicle population in low speed front to rear collisions

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ABSTRACT

Rear impact collisions are mostly low severity, but carry a very high societal cost due to reported symptoms of whiplash and related soft tissue injuries. Given the difficulty in physiological measurement of damage in whiplash patients, there is a significant need to assess rear impact severity on the basis of vehicle damage. This paper presents fundamental impact equations on the basis of an equivalent single vehicle to rigid barrier collision in order to predict relationships between impact speed, maximum dynamic crush, mean and peak acceleration, time to common velocity and vehicle stiffness. These are then applied in regression analysis of published staged low speed rear impact tests. The equivalent mean and peak accelerations are linear functions of the collision closing speed, while the time to common velocity is independent of the collision closing speed. Furthermore, the time to common velocity can be used as a surrogate measure of the normalized vehicle stiffness, which provides opportunity for future accident reconstruction.

1. Introduction

The injuries arising from rear impact are mostly low severity since the collision speed is generally much lower than for frontal impact. Nonetheless, due to its frequency, this crash mode results in 30% of automotive-related trauma, and low-severity rear impact accounts for more long-term injury than any other crash mode (Viano, 2002). Accordingly, the annual cost of whiplash type injuries is billions of dollars in the US alone (Viano and Olsen, 2001).

The most significant rear impact related injuries are a set of soft tissue injuries frequently called whiplash associated disorders (WAD), which remain surprisingly poorly understood, despite significant research efforts. Injury mechanisms proposed include a hyperextension mechanism, an eccentric contraction mechanism, a hydrodynamic mechanism, and combined mechanisms of axial loading, shear force and bending (Yoganandan et al., 2013). This plethora of proposed mechanisms debated in the literature indicates the lack of consensus in relation to the precise biomechanical causes of whiplash. Nonetheless, the primary cause is relative motion between the torso and the head, driven by a combination of the vehicle acceleration time history and the interaction of the occupant with the seat and other vehicle components.

A particular challenge for low severity rear impact injuries is the tangible measurement of injury, though recent findings suggest that MRI is capable of quantifying neuromuscular degeneration in chronic whiplash (Elliott et al., 2014). A recent review has concluded that there is growing evidence that a claimant's physiological and psychological stress response is a very significant factor in persistent symptoms following whiplash injury (Worsfold, 2014). Similarly, given the legal context of whiplash, a toolkit for identifying cases with a crash severity so low that the chances of whiplash injury are remote has been proposed (Moser et al., 2011).

Given the difficulty in physiological measurement of damage in whiplash patients, there is a significant need to assess rear impact severity on the basis of vehicle damage. In particular, fundamental principles of injury biomechanics dictate that it is strongly desirable to have methods to assess the magnitude of the acceleration pulse as well as the velocity change imposed on the struck vehicle. However, for very low speed cases, there is frequently no visible damage to the vehicle at all, despite the fact that whiplash symptoms are frequently reported.

There have been previous modeling approaches to reconstructing low velocity rear impact collisions. As reviewed by Scott et al. (2010, 2012), these approaches have broadly followed either the

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differential equation approach (Thomson and Romilly, 1993; Ojalvo and Cohen, 1997; Ojalvo et al., 1998; Brach 2003; Scott et al., 2010, 2012) which require explicit definition of the effective stiffness of the two-vehicle system but which provide acceleration time histories, or a momentum energy restitution approach (Bailey et al., 1995; Cipriani et al., 2002; Happer et al., 2003) which does not require an estimate of vehicle stiffness, but consequently limits predictions to velocity change rather than acceleration time history.

From an injury biomechanics perspective, the differential equation approach which provides acceleration time histories is far preferable, but the variety of bumper designs make the effective stiffness of a specific vehicle pair involved in a rear end collision difficult to predict. There is therefore the need for a generic reconstruction model which can account for mean and variation.

The recent work by (Scott et al., 2010, 2012; Bonugli et al., 2014; Funk et al., 2014) has shown that, when experimental knowledge of the combined bumper deformation behavior is known for a specific vehicle pair, the impact response for a specific collision can be found. However, the tests they completed showed non-linear and variable bumper stiffnesses, and the approach yields nontrivial errors in the coefficient of restitution. Furthermore, for assessment of visible damage, a single quasi static test is not sufficient.

In Switzerland, the AGU accident research group has performed a set of 45 unbraked staged full overlap and over-ride/under-ride rear impact collisions with an impact speed range of 8–27 km/h (AGU, 2014). Fig. 1 shows the non-linearity and variability of the resulting acceleration time curves, leading to the preliminary conclusion that there is so much variability in these kinds of collisions due to vehicle design variations and impact configuration that it is impractical to develop a generic model.

However, further analysis shows that significant trends can be identified in this dataset. Accordingly, the goal of this paper is to present the fundamental impact equations to predict relationships between impact speed, maximum dynamic crush depth, mean and peak acceleration, time to common velocity and vehicle stiffness, and to use these as a basis for regression analysis for the 45 low speed rear impact cases published by AGU (2014) for full overlap and over-ride/under-ride cases. This approach provides considerable insight into the mechanics of low speed rear impact collisions.

2. Methods

There are two main components to the work performed:

1. Fundamental collision modeling to inform the regression analysis of the staged test data.
2. Regression analysis of staged low speed front to rear collisions published by AGU (2014).

2.1. Fundamental collision modeling to inform staged tests regression analysis

Here fundamental impact modeling is used to develop relationships between impact speed, crush depth, mean and peak acceleration and vehicle stiffness. These form the basis for regression analysis for the staged low speed rear impact tests published by AGU (2014). A detailed multibody or finite element modeling approach is not necessary, since a considerable body of experimental data is freely available through the AGU. The fundamental modeling approaches show which functional forms the regression analysis of the measurable impact variables should take.

2.1.1. Front to rear collision of two vehicles

When two vehicles (m_1,m_2) are subject to a collinear impact, the system can be regarded as equivalent to a single vehicle impacting a rigid barrier. The equivalent mass m_{eq} impacts the rigid barrier at the collision closing speed V_{ccs} and rebounds at the separating speed V_{sep} given by the following equations from conservation of momentum and conservation of energy considerations:

$$m_{eq} = \frac{m_1 \times m_2}{m_1 + m_2}, \tag{1}$$

$$V_{ccs} = V_{eq} = V_1 - V_2, V_{sep} = V'_2 - V'_1, \tag{2}$$

where V_{eq} is the pre-impact velocity of the equivalent mass and this is equal to the collision closing speed, V_{ccs}, of the colliding pair where V_1, V_2 are the pre-impact velocities of the two vehicles.

The equivalent acceleration a_{eq} and each vehicle acceleration (a_1, a_2) are related as follows:

$$a_{eq} = a_2 - a_1,$$

$$a_1 = \frac{m_2}{m_1 + m_2} a_{eq},$$

$$a_2 = \frac{m_1}{m_1 + m_2} a_{eq}. \tag{3}$$

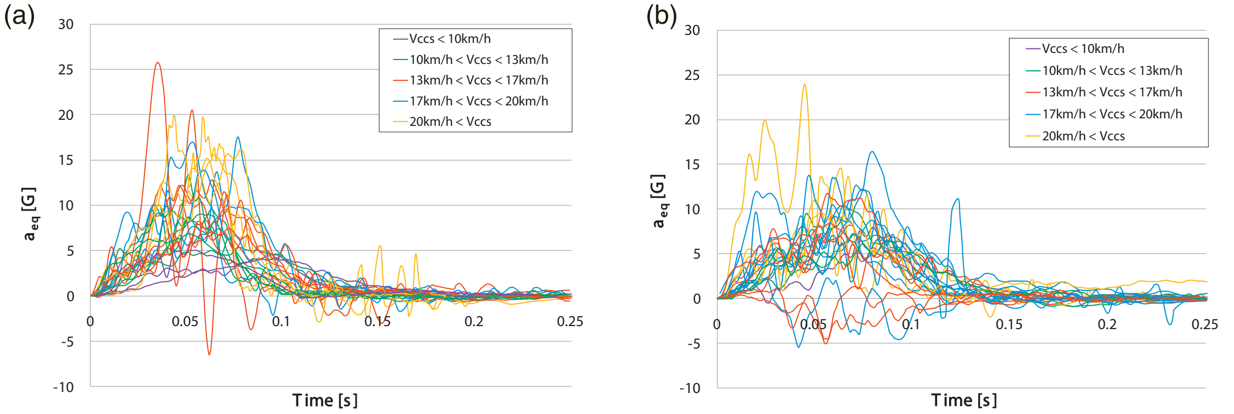

Fig. 1. Equivalent acceleration–time histories of the two vehicles collisions (front to rear collisions) published by AGU (2014) for (a) full engagement test and (b) under-ride/over-ride tests.