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Evaluation and characterization of crash-pulses for head-on collisions with varying overlap crash scenarios

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Abstract

Activation time for activating the occupant restraint systems (airbag and seatbelt) is very critical for an optimal safety action. A crash-pulse is the deceleration of the vehicle measured during in a crash. The shape, slope, maximum deceleration and duration of the crash-pulse provides significant information over the nature of occupant motions during in-crash phase and hence the crash severity. The above parameters of the crash-pulse not only depend on the mass and impact velocity but also on the crash configuration (position of impact, overlap, relative approach angle etc.).
This study focuses on analysis and characterization of crash-pulses in head-on collision cases with varying overlap configurations. The paper describes causes for occupant injuries during a crash, crash-pulse and its important physical parameters, and different methodologies used to analyse the crash-pulse. Finite element simulation method is used to study the crash-pulses from different crash configurations. A new severity index that has direct influence on the occupant kinematics is defined. The results show that the steep decrease of crash-pulse for small overlap configurations (less than 25 percent of vehicle width) lags by 20 to 25 milliseconds as compared to configurations with large overlaps. The shape of the crash-pulse also changes for crash scenarios with different overlap configurations. The results, discussion and conclusion sections of this paper provide a summary of crash behaviour of varying overlap crash scenarios and insights that can be used for deployment of restraint systems.

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Keywords: Crash severity; Head-on collision, Frontal crash; Crash-pulse characterization

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1. Introduction

European Union plans to reduce the number of road deaths to almost zero by 2050 (European Union 2018). In order to move a step closer to this goal, further development of current safety systems is essential. One of the methodologies adopted by the automotive industry is early activation of the occupant restraint systems based on pre-crash information.

Advanced driver assistance systems and partially automated driving systems are equipped with sensors, which can provide information about the crash configuration. If the information about the crash severity for different crash

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configurations is available, then the best occupant protection strategy can be selected and the suitable restraint systems can be triggered at an optimal time. This highlights the importance of studying the vehicle crash-pulse and its severity under different crash configurations. Understanding the behavior of crash-pulses for different crash scenarios has an important role in prediction of the optimum restraint strategy using pre-crash information.

In Germany, the mortality rate for a front crash scenario is 21.27 percent, which is the one of the highest among the crash scenarios (Statistisches Bundesamt 2016). Governmental agencies, research and insurance institutes are continuously evaluating vehicles against various safety threats to improve occupant safety. Studies by these agencies and institutes highlight that the severity in frontal vehicle-to-vehicle crash depends on the overlap (i.e. the percentage of the width of the vehicle in contact with the other vehicle). In addition, these studies draw attention to critical crash scenarios with less than 25 percentage overlap having more fatality rates. Unfortunately, previous studies are focused on vehicle crash scenarios with 25 percent overlap and does not cover crash scenarios with the complete overlap range (Saunders et al. 2012; Saunders and Parent 2013).

Hence, the authors decided to investigate the head-on collision with varying overlap crash scenarios using finite element simulations. The goal of the study is to characterize the crash-pulse for different crash scenarios, which can be used in the next stage for predicting crash severity and decisions on triggering the occupant restraint systems.

2. Vehicle crash

A vehicle crash is a very complex event and the severity of a vehicle crash depends on many different crash parameters like impact velocities of vehicles, mass of the vehicles, vehicle structure, overlap of the vehicles etc. Figure 1. shows a generic in-crash phase with the three collision events that occur in this phase. The first collision event occurs when a vehicle collides with the opponent. The time at which vehicle first contacts its opponent is considered as T_0. After this time T_0, the vehicle starts to decelerate. The fast deceleration of the car from the first collision will cause the occupant to move forward due to inertia. The second collision occurs when the occupant hits the interior of the car. Similar to the occupant movement due to the deceleration of the car, the internal organs like brain, liver etc. move due to inertia and collide against the human body structure. This collision is referred to as internal collision. The three types of collisions are the root causes of the occupant injuries.

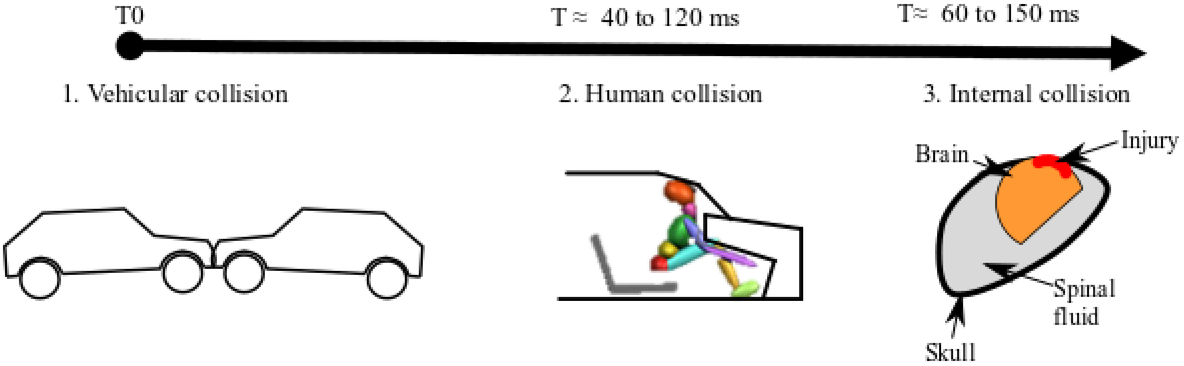


Fig. 1. Generic time-line of in-crash phase

2.1. Crash management structure and occupant restraint systems

The front vehicle structure is designed to absorb the energy in the vehicle crash. Table 1. describes the energy absorbed by the parts of the front crash management structure with different crash velocities. The absorption of the energy decelerates the vehicle in a softer way as compared to rigid collision. This lowers the acceleration of the occupant to some extent which is not sufficient to save the occupant from fatalites and injuries in a moderate to high speed crash (approximately above crash velocity of 25 km/h).

Use of occupant restraint systems such as seatbelt, belt pre-tensioner and airbag has saved many lives in a vehicle crash. Seat belt and belt pre-tensioner restricts the forward motion of the occupant and thereby reduces the acceleration of the occupant, while the airbag ensures a softer contact of the occupant with the interior of the car. The trigger or activation time of the occupant restraint systems is very critical. An early activated airbag is similar to a vehicle without an airbag. On the other hand, delayed activation can lead to adverse injuries from the explosive inflation of the airbag (Wallis 2002).

A "5 inches – 30 milliseconds" rule is commonly used for deciding the airbag triggering time as a general rule of thumb (Huang 2002). A common driver-side airbag requires 30 milliseconds for complete inflation while the distance between the airbag and the occupant is about 5 inches. This rule describes the airbag should be triggered at about 30 milliseconds before the time required by the occupant to move 5 inches in longitudinal direction. Hence the airbag activation time depends on the motion of occupant (occupant velocity), which varies depending on the crash configuration and the crash parameters mentioned above. The triggering of the belt pre-tensioner should also be synchronous with the airbag system so that the occupant comes in contact with the airbag at proper time.

Table 1. Generic energy absorption distribution of front crash management structure (European Aluminium Association 2011)

Parts of Front crash management structure	Low velocity (2.5 to 8 km/h)	Medium velocity (15 to 16 km/h)	High velocity About 60 km/h
Pedestrian Foam	20-60%	5-20%	2-4%
Bumper beam	30-100%	10-100%	2-3%
Crash box	2%	20-75%	4-6%
Other structures	2%	3%	<1%

Present passive safety systems for frontal crash are equipped with sensors at different locations on vehicle structure. These sensors measure the deceleration of the vehicle (crash-pulse), calculate various physical parameters from this crash-pulse (an estimation of occupant motion) and based on these parameters, the time for airbag activation is decided.

2.2. Crash-pulse

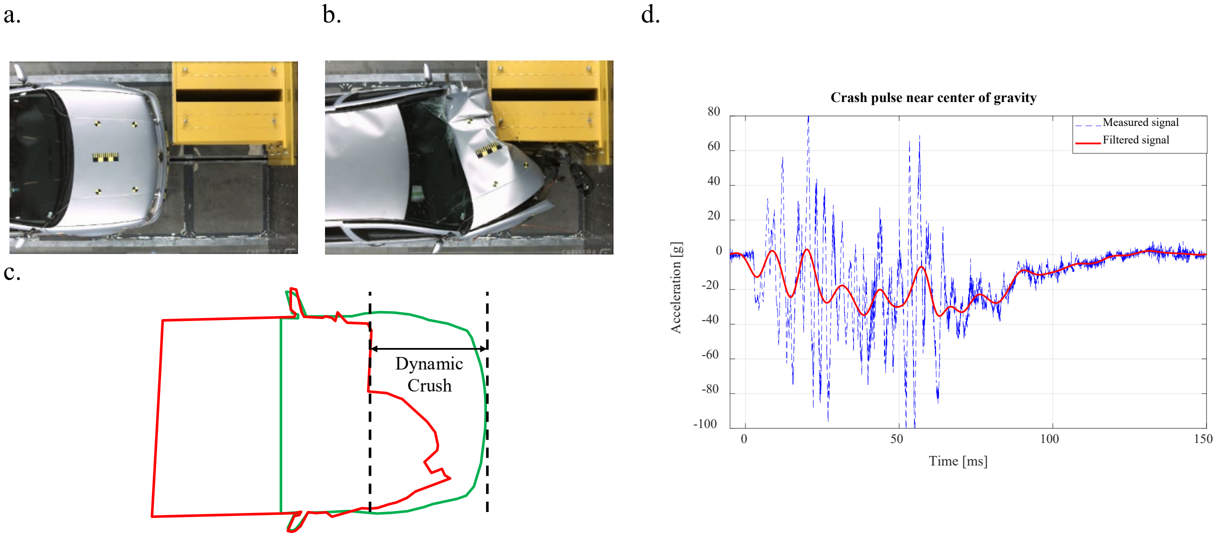


Fig. 2. (a) Frame at -1 millisecond (b) Frame at 81 milliseconds; (dynamic crush- maximum deformation); (c) Overlay of vehicle outline at two frames; (d) Crash-pulse measured near center of gravity

Crash-pulse describes the vehicle motion during the in-crash phase i.e. the deceleration of the vehicle at different sample times. This deceleration can be measured at different locations on the vehicle structure based on the sensor configuration. The sensor closest to the center of gravity gives the real physical behavior of the in-crash motion of the complete vehicle structure. Figure 2. shows two frames from the high-speed video and the crash-pulse of the 40% overlap test at 64 km/h impact velocity against rigid barrier. This test was conducted in the crash test facility at CARISSMA, Technische Hochschule Ingolstadt. The vehicle deceleration has direct influence on the occupant kinematics and thus crash-pulse is a crucial factor for decision of triggering the restraint systems (Cheng 2006; Grimes and Lee 2000). Simplified versions of the crash-pulse (triangular pulse, average constant, half sine wave etc.) are used as inputs to investigate occupant kinematics either with sled tests or with simulations.

From a crash-pulse, different physical parameters can be calculated. Some of the important parameters majorly used for activation decisions of restraint systems are explained below.

2.2.1. *Change in velocity* (*ΔV*): Change in velocity is one of the most important parameters, which has a direct influence on crash severity and plays a vital role in deployment of occupant restraints systems. Almost 90% of the frontal driver-side airbags are deployed when a change in the velocity is above 24 km/h (Gabler and Hinch 2008). All the automotive manufacturers use this parameter in the decision algorithm of the restraint systems. It is one of the most important parameters of the national crash database and is either extracted from the Event Data Recorder (EDR) or calculated by the accident reconstruction engineers after the crash.

2.2.2. Displacement (x): Displacement is calculated by integrating the deceleration signals twice. It gives an estimate of the overall maximum deformation (dynamic crush), actual deformation and rebound. Some of the automotive manufacturers use change in displacement as a threshold to start the restraint systems algorithm.

2.2.3. *Jerk (J):* Jerk is the rate of change of deceleration signals. A high value of jerk signifies a sudden deceleration of the vehicle and hence a corresponding sudden acceleration of the occupant. The deceleration signal from the sensors is very noisy. Hence, jerk is usually calculated at predefined sample times (every 5 to 15 milliseconds) after filtering the deceleration signals. This parameter is used by some of the automotive manufacturers to identify the sudden deceleration of the vehicle.

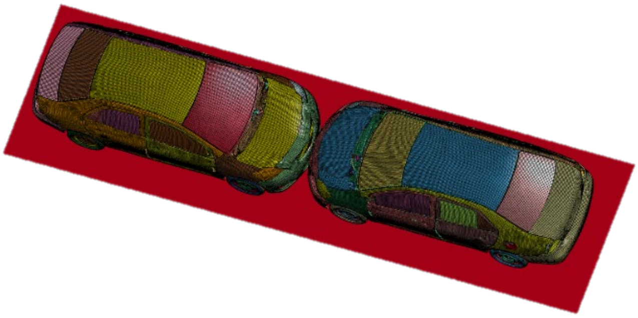
2.2.4. *Absorbed energy (E):* During crash, the kinetic energy of the vehicle is absorbed by deformation of vehicle parts. Change in kinetic energy is another measure of the severity, usually used by the accident reconstruction engineers. This parameter includes the influence of the mass of the vehicle.

3. Methodology

The methodology to acquire the crash-pulse for different crash scenarios can be classified into two major groups, crash tests and simulations. Performing crash tests require enormous costs and labor and hence it was not feasible. There are two basic approaches to simulate a vehicle crash scenario. The first approach is to model the vehicle and its important elements such as mass, spring and damper elements. This methodology is commonly referred as Lumped Parameter Modeling (LPM). LPM is simple and requires low computer resources. But it requires the physical values of the elements such as stiffness and damping coefficient as inputs. This approach lacks the ability to represent the geometrical and exact material behavior under different vehicle loading conditions. The second approach is called as Finite element Method (FEM). This method consumes more time and resources as compared to LPM. However, it incorporates the geometry, different material models, boundary conditions and hence the ability to reproduce the crash-pulse similar to a real-crash scenario. The major challenge in FEM simulation is to develop the vehicle model and its validation.

For analyzing the crash-pulses with varying overlap percentage, it was decided to simulate these crash scenarios using finite element method. Figure 3. shows the vehicle model with the important information of the model. This model represents a Toyota Yaris (construction year: 2010), developed by Center for Collision and Safety and Analysis, George Mason University and is freely available for research use. The vehicle model is modified in LS-Dyna simulation software to simulate a head-on collision with two identical vehicles. Constant velocity was given to one vehicle while the other vehicle was stationary. An initial gap of 2 mm distance was maintained in all the simulations to avoid errors arising from contact of the elements before the simulation. The deceleration values at the center of gravity from the simulation were selected for analysis.

Vehicle model properties	
Number of parts	919
Number of nodes	393165
Number of elements	378376



Property	Actual vehicle	Vehicle model
Weight [kg]	1078	1101
C.G. x [mm]	1022	1025
C.G. y [mm]	-8.3	-3.0
C.G. z [mm]	558	557

Fig. 3. Toyota Yaris- head-on collision finite element model and some important details about the model

4. Results and discussions

Figure 4 a. shows the energy diagram of a crash simulation. A vehicle crash simulation is very complex method with many different parts represented as elements, material models, contacts, boundary conditions and load curves. Total energy and hourglass energy is a good measure of the quality of simulation. Both should not change more than 10 percent in a simulation. It can also be seen that the kinetic energy is converted into internal energy (energy absorbed in deformation). These checks were performed for all the simulations to ensure their reliability.

The deceleration signals from the simulation are similar to the one measured in real-crash test. These signals contain high frequency physical events, which are not required for analysis and characterization of the crash-pulse. Therefore, it is a common practice to filter the deceleration signals. During post processing of the crash-pulse from the simulation a second order low-pass butterworth-filter with 180 Hz cut-off frequency was used with forward-reverse filtering technique. This filter is similar to SAE-108 or CFC-108 filter commonly used in the field of automotive crash analysis.

Figure 4 b. shows the results of the simulation with 64 km/h approach velocity with different overlap conditions. It can be seen from the velocity diagram that the maximum change in velocity (ΔV_{max}) for crash simulations with different overlaps can be grouped in two different classes. One class consists of simulations with ΔV_{max} approximately equal to 10.5 m/s, while the other consists of those simulations with a ΔV_{max} value of about 9.2 m/s. The maximum change in velocity is a good overall approximation of the crash severity for the occupant movement in longitudinal direction.

The activation of the frontal airbag and seatbelts is influenced by only x-direction deceleration of the vehicle. Hence, only x-direction deceleration values are considered in the study. The crash-pulses shown in figure 4 c. give a more detailed view of the crash behavior and an estimate of occupant's movement. All the crash pluses are divided into three phases in figure 4 c. as described below:

1. Deceleration phase (Some crash pulses have two deceleration phases a and b)
2. Constant acceleration phase
3. Acceleration phase.

It can be seen that for the crash with 100 percent overlap, the deceleration phase lasts up to 15 milliseconds. Next, the deceleration value fluctuates about the maximum deceleration for about 40 milliseconds and then rises back to zero in the acceleration phase. As the overlap reduces, the deceleration phase of the crash-pulse can be divided into two sub-phases with different slopes (phase a and phase b). In some of the crash-pulses, the constant acceleration phase (phase 2) was not present. The reason for this trend and change in the shape of crash-pulse is as in the case of a low overlap crash, where the vehicles initially for some period of time (about 30 to 40 milliseconds) collides with the soft materials like plastic bumper, lights and avoids the contact with the bumper beam. After this time, the rigid structures of the vehicles contact with each other and cause a steep deceleration.

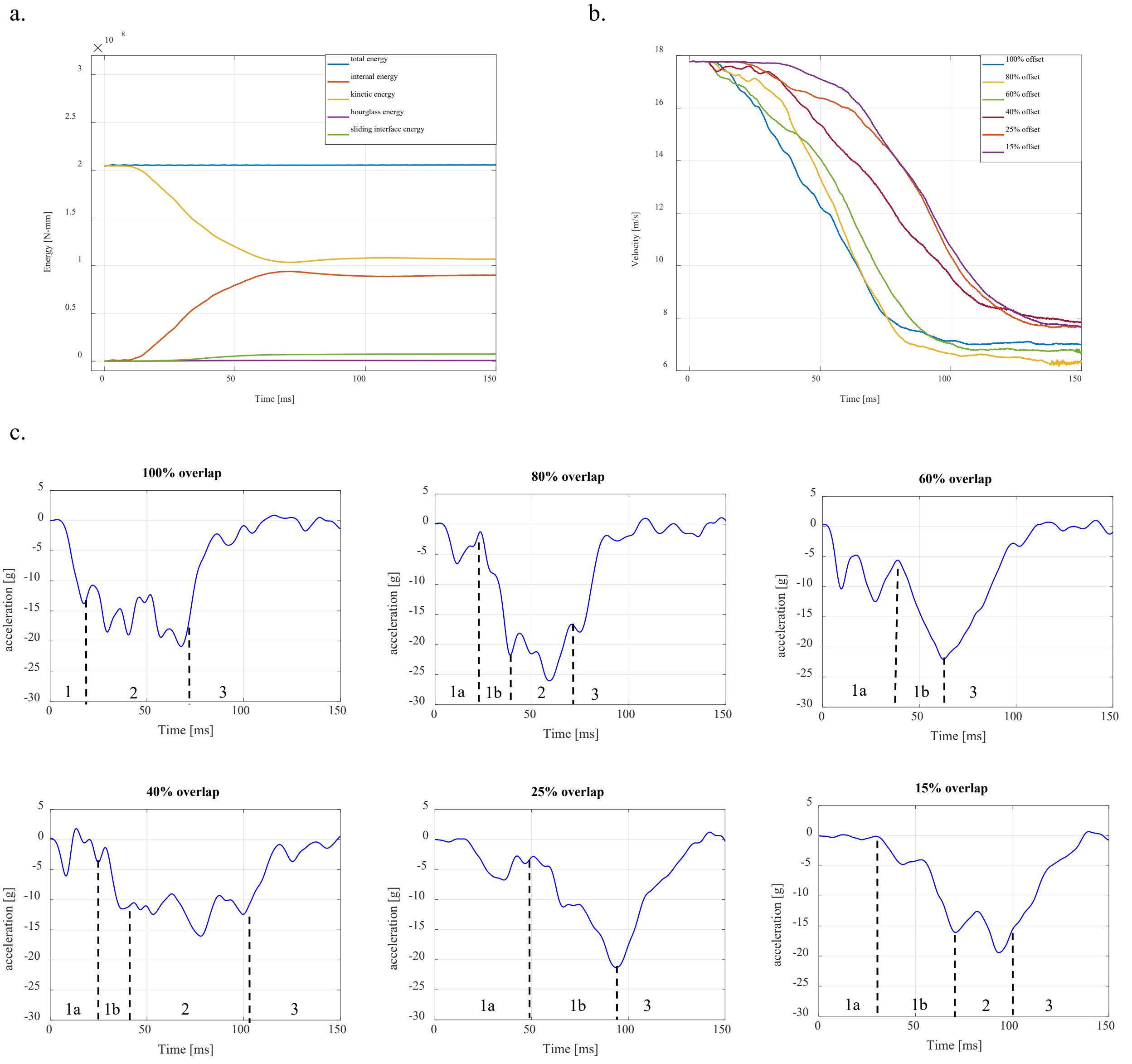


Fig. 4. (a) Energy diagram; (b) Velocity curves with different overlap configurations for 64 km/h approach velocity simulations; (c) Crash-pulses with different overlap configurations for 64 km/h approach velocity simulations (deceleration signals are filtered with low-pass butterworth filter)

5. Characterization of crash-pulse

Crash-pulse characterization is a process of representing the deceleration values measured in a vehicle crash by a simplified mathematical model or equation. The primary objective of the characterized crash-pulse is to retain the information required to calculate the parameters with required accuracy for the intended application. At the same time, the characterized mathematical model should involve as minimum variables as possible. The common basic crash-pulse approximations are listed below.

- Square wave approximations
- Trapezoidal wave approximation
- Bi-slope approximation
- Half sine wave approximation
- Haver sine wave approximation

The objective of all the above approximations is to use the crash-pulse as an input to the actuators for testing occupant kinematics in a sled-test or as input for simulations. With the above approximations, some of the important information about the occupant kinematics is lost. Moreover, a single approximation method cannot represent all the shapes of the crash-pulses for varying overlap configurations of the intended study, as can be observed in figure 4 c. The deceleration phase divides itself in two sub-phases as the overlap is reduced. Hence, it was decided to use the approximation of summation of two sine curves. Figure 5 displays the crash pulse of two different shapes and their non-linear regression fits. It can be observed that the shape of the crash pulse is retained better by the summation of sine wave fit as compared to Haver sine wave fit (one of the most commonly used).

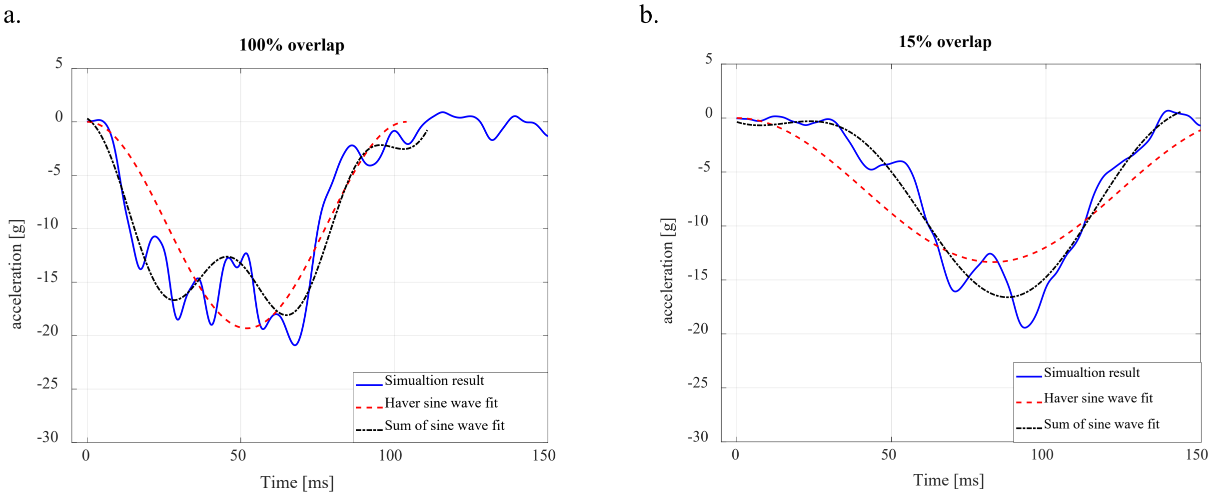
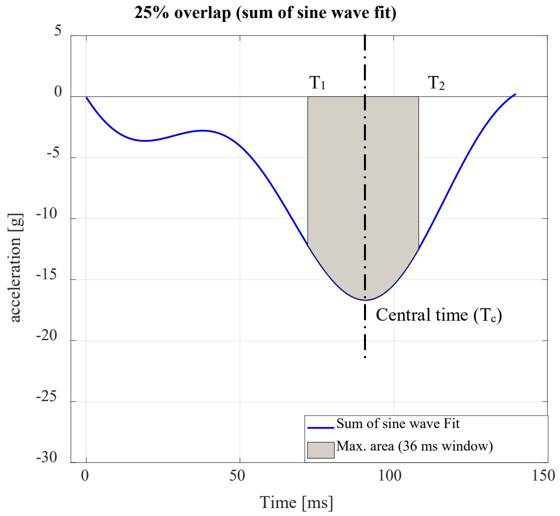


Fig. 5. Results of fitting mathematical approximations on crash-pulse (a) 100 percent overlap configuration; (b) 15 percent overlap configuration

Consider the two cases, one with 100 percent overlap and the other with 15 percent overlap. For the crash with 100 percent overlap, the vehicle decelerates rapidly after 5 milliseconds and hence the occupants would also move rapidly forward in the occupant compartment. At this moment of time (after 5 milliseconds up to 30 milliseconds), for 15 percent overlap crash, the deceleration is almost constant at about 0.1 g which implies that the occupants experience a very low forward acceleration. Therefore, the activation times of frontal restraint systems for both the cases should vary considerably (approximately 25 to 35 milliseconds) for optimum restraint effect. Considering only frontal restraint systems, the crash with 100 percent overlap is more severe than with lower overlap crash scenarios. This can also be clearly observed in figure 5.



Severity index in x-direction is given by,

$$SI_x{}^w = \frac{maximum\ area\ for\ time\ window}{central\ time}$$

$$= \frac{\left\{\int_{T_1}^{T_2}[(a_1 \cdot \sin(\omega_1 \cdot t\ + \varphi_1) +\ a_2 \cdot \sin(\omega_2 \cdot t\ + \varphi_2)]\right\}^{max}}{T_c} \qquad (1)$$

Fig. 6. Description of Severity Index in x-direction

Many studies have considered area enclosed by the crash-pulse, i.e. maximum change in velocity (ΔV_{max}) as a direct measure of crash severity or activation timings of restraint systems (Gabauer and Gabler 2006; Gabler and Hinch 2008). This approach does not consider the rate of change or maximum deceleration of the crash pulse and neither their corresponding times. In this study, an approach similar to calculate the head injury of the occupant-dummy (Head Injury Criteria (Prasad and Mertz 1985)) is used. This approach uses the maximum area bounded by the crash pulse for a predefined time window. In addition to the maximum area, its central time (T_c) was also considered. It is the time corresponding to the centroid of the enclosed window-area of the curve. Note that this point may not be the average of the window start (T_1) and window end (T_2). It depends on the shape of the curve in the maximum window region.

The new parameter obtained from the ratio of the maximum area to the central time is termed as 'Severity Index in x-direction ($SI_x{}^w$)' as shown in figure 6 (here, subscript 'x' refers to x-direction and superscript 'w' refers to the window period in milliseconds). This maximum area is calculated using sliding window approach. The window of the maximum area lies in close proximity of the maximum deceleration of crash-pulse. Hence, the time corresponding to the maximum deceleration is a good initial point for the calculation. The time for the maximum deceleration can be mathematically derived as shown below.

The equation of deceleration with a summation of two sine waves is given by,

$$a(t) = a_1\ \sin(\omega_1 t + \varphi_1) + a_2\ \sin(\omega_2 t + \varphi_2) \qquad (2)$$

where, $a(t)$ is the deceleration signal

a_1, ω_1 and φ_1 represent the maximum amplitude, frequency and phase shift of first sine wave

a_2, ω_2 and φ_2 represent the maximum amplitude, frequency and phase shift of second sine wave

Differentiating (2) with respect to time and equating to zero

$$\dot{a}(t) = a_1\ \omega_1 \cos(\omega_1 t\ + \varphi_1) + a_2\, \omega_2\ \cos(\omega_2 t +\ \varphi_2) \qquad (3)$$

We know that a_1, ω_1 , a_2 , and ω_2 cannot be zero. Hence, we obtain the following equations,

$$\cos(\omega_1 t\ + \varphi_1) = 0 \qquad (4)$$

$$\cos(\omega_2 t + \varphi_2) = 0 \tag{5}$$

Cosine wave is zero at odd multiples of $\pi/2$,

$$\omega_1 t + \varphi_1 = (2k_1 + 1)\,\pi/2 \tag{6}$$

$$\omega_2 t + \varphi_2 = (2k_2 + 1)\,\pi/2 \tag{7}$$

where, $k_1, k_2 \in \{0, 1, 2, 3 \ldots\ldots..\}$.

Time at maximum deceleration is given by,

$$t = ((2k_1 + 1)\,\pi/2 - \varphi_1)/\omega_1 = ((2k_2 + 1)\,\pi/2 - \varphi_2)/\omega_2 \tag{8}$$

By substituting the k_1 values for the slower time curve, the first positive time value where the above condition satisfies can be evaluated.

Table 2 Severity index parameters for crash simulation with different overlap configurations

Overlap configuration [%]	$Area_{max}^{36}$ [m/sec]	Central Time (T_c) [sec]	Severity Index (SI_x^{36}) [m/sec^2]
100	0.6370	0.0649	9.8
80	0.8596	0.0562	15.3
60	0.7002	0.0661	10.6
40	0.4688	0.0715	6.6
25	0.5880	0.0908	6.5
15	0.5859	0.0876	6.7

Table 2 displays the values of the parameters calculated from the non-linear regression fit of simulations with different overlap configurations. The higher the severity index, the closer the activation timings of the restraint systems to the time at first contact (T_0). It can be observed that for low overlap crash configurations the severity index is less compared to the high overlap configurations, also the central time is about 15 to 25 milliseconds later.

6. Conclusion

In this study, we propose a new crash severity index, which is specific for the frontal restraint system. The simulation results show that the lower overlap crash configurations have lower severity for frontal airbag systems. In addition, for these crash scenarios, the restraint systems should be triggered about 15 to 25 milliseconds later as compared to the crash scenarios with high overlap. Previous studies and statistics predict that more number of occupants is injured in low overlap crash scenarios as compared to large overlap scenarios. One of the reasons for these injuries is lack of restraint systems towards the lateral or diagonal movement of the occupant. Another reason is higher intrusion level in the occupant safety cell. These two reasons can be treated with separate severity indexes and decision on their respective restraint systems can be taken separately (curtain airbag for diagonal movement of occupant and knee airbags to avoid injuries from intrusion).

The crash pulses from the finite element simulation results show different shape behavior for different overlap configurations of vehicle-to-vehicle crash. This study shows that sum-of-sine wave approximation is a better approximation as compared with the basic approximation models. This model is an important milestone for further studying the crash-pulse under other crash-scenarios.

Acknowledgements

The vehicle model used in the study is free for research use and can be downloaded from the website of Center for Collision Safety and Analysis (CCSA), George Mason University, Virginia, USA. The authors appreciate and thank CCSA for the availability of the validated vehicle model.

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