

Assessment of the Accuracy of Certain Reduced Order Models used in the Prediction of Occupant Injury during Under-Body Blast Events

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ABSTRACT

It is of considerable interest to developers of military vehicles, in early phases of the concept design process as well as in Analysis of Alternatives (AoA) phase, to quickly predict occupant injury risk due to under-body blast loading. The most common occupant injuries in these extremely short duration events arise out of the very high vertical acceleration of vehicle due to its close proximity to hot high pressure gases from the blast. In a prior study [16], an extensive parametric study was conducted in a systematic manner so as to create look-up tables or automated software tools that decision-makers can use to quickly estimate the different injury responses for both stroking and non-stroking seat systems in terms of a suitable blast load parameter. The primary objective of this paper is to quantitatively evaluate the accuracy of using such a tool in lieu of building a detailed model for simulation and occupant injury assessment.

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INTRODUCTION

Underbody blasts have become one of the most widespread reasons for warfighter casualties in recent wars [1, 2, 3]. Spinal injuries to occupants have particularly increased in theater from these roadside blast incidents, followed by tibia and lower leg injuries. To support the design and development of military ground vehicles, mine blast underbody hull kits and mine blast seats, a suite of underbody modeling methods were quickly developed [4, 5, 6, 7, 8, 9, 10, 11]. These modeling and simulation (M&S) methodologies are being continuously enhanced with ever-increasing capabilities to predict vehicle structural and occupant injury responses, including fast running models for the same [16, 17].

It is of considerable interest to developers of military vehicles, in early phases of the concept design process, to quickly predict occupant injury risk due to under-body blast loading [12, 16]. The most common occupant injuries in these extremely short duration events arise out of the very high vertical acceleration of vehicle due to its close proximity to hot high pressure gases from the blast. A typical blast vertical acceleration history which is predominantly triangular shaped in nature is shown in Fig 1, and is often measured at a rigid location on the military vehicle to serve as a representative measure or a "signature" of the blast severity, and is often referred to as the "blast pulse". This can be thought of as being

analogous to the crash pulse used in the automotive industry to serve as the loading that is experienced in the fore-aft direction by the structural components as well as the occupants in the vehicle interior. For example, the seats experience the pulse as a load at their structural attachment points. Other than the obvious difference in sign and direction (frontal crash results in vehicle deceleration in the fore-aft direction, while underbody blasts result in vehicle acceleration in the vertical direction), there are two other major differences between the blast pulse, and its frontal safety crash counterpart, namely:

- the peak acceleration - the blast pulse tends to be 5-10 times *larger* in magnitude, and
- the duration of the pulse - the blast pulse tends to be 3-5 times *shorter* than its crash counterpart.

As a common feature, both pulses serve as design criteria for development of seats, restraints and other safety features, and are even measured in a similar manner. The frontal crash pulse is usually the average fore-aft deceleration measured at one or more accelerometers at the stiff B-pillar/Rocker joint areas, while the blast pulse is usually the average vertical acceleration measured at one or more accelerometers at the stiff pillar/roof joint areas.



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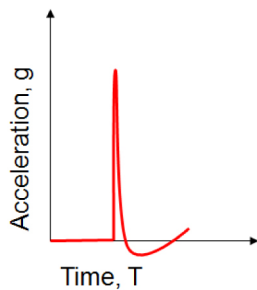


Fig. 1. A typical blast pulse

There has been a continual quest in the blast community of practice to define one or more loading parameters from the “blast pulse” that would by themselves, or in combination thereof, serve as indicators of blast severity and therefore occupant injuries, similar to the crash pulse scenario. For example, in automotive frontal crashes, the peak value in the crash deceleration pulse is one quantity that directly correlates to occupant injuries, everything else being constant. In the past, several similar loading parameters have been proposed for blast pulses. Of these, the design community has mostly used change in velocity Δv , or to a much lesser extent, peak acceleration G_{peak} , to determine the severity of, and classify any given blast pulse.

BLAST LOAD INDICATORS/DESCRIPTORS

In the past, several blast loading parameters have been proposed, alone or in combination, to serve as indicators or predictors of occupant injuries[16]. Some examples of these are:

1. magnitude of the peak acceleration, G_{peak} in g's,
2. time duration of pulse, T in milliseconds (ms),
3. rate of onset of acceleration, $\dot{G}$ in g/ms,
4. change in velocity, Δv in m/s
5. effective-g[13] (slope of the velocity profile) G_{eff} in g's,
6. specific power[14], SP ($G_{peak} * \Delta v$) in g-m/s, or m^2/s^3 .

Of these, the Survivability design community has largely used change in velocity Δv , or to a lesser extent, peak acceleration G_{peak} , to describe the severity of, and classify any given blast pulse.

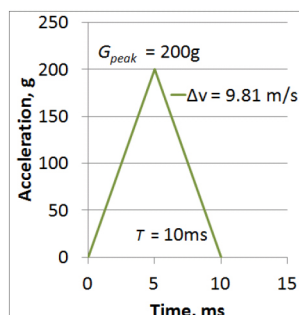


Fig. 2. An example triangular blast pulse (Acceleration profile)

Fig. 2 shows an example of a blast pulse with a peak acceleration of 200g and 10ms duration. The corresponding velocity profile is shown Fig. 3, along with illustrations of how Δv , G_{avg} and G_{eff} are calculated for the same.

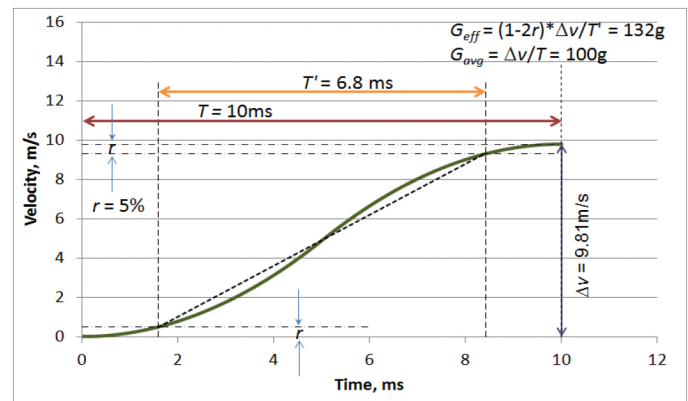


Fig. 3. An example triangular blast pulse (velocity profile) Definition of effective-g [15] is also shown

BACKGROUND OF PRIOR STUDY [16]

Blast Simulation Model

Two setups of the dynamic simulation model of a vertical blast loading simulator are shown in Fig. 4 and 5. In the first setup, a 50th percentile Humanetics' Finite Element (FE)-based Hybrid-III Anthropomorphic Test Dummy (ATD) model (v7.16) in LSDYNA® format is seated on a rigid finite element seat with a five point seat belt as shown in Fig. 4. This seat is rigidly placed on a vertically sliding platform (not shown in figure) where the blast pulse was input as base excitation. A typical run time for a FE-based simulation lasting 100ms duration is about two hours using 16 processors on an Intel x86-64 based Linux server.

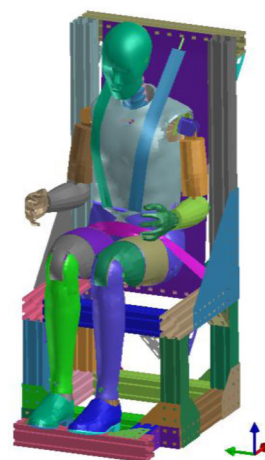


Fig. 4. LSDYNA dynamic simulation model including Humanetics v7.1.6 Hybrid III 50th percentile ATD model

In the second setup, a vertical blast loading sled is constructed [13] using finite elements of assigned rigid material. A MADYMO® rigid multibody (RMB) based model of the 50th percentile Hybrid-III ATD (Q version) seated on a RMB seat.

with a three point seat belt, is attached to a vertically sliding platform where the blast pulse was input as base excitation. A typical run time for a RMB-based simulation lasting 100ms duration is about 20 minutes using a single processor on an Intel x86-64 based Linux server.

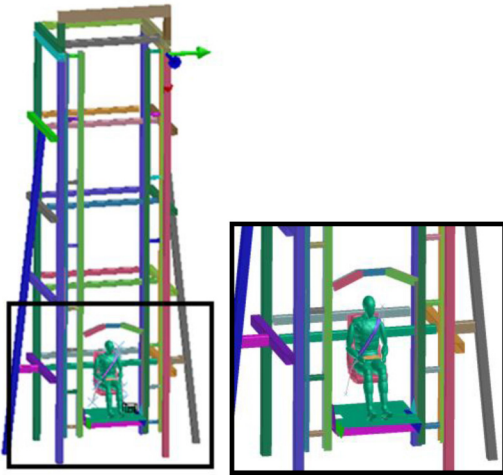


Fig 5. MADYMO dynamic simulation model including Q-version of Hybrid III 50th percentile ATD



Fig 6. Photograph of a typical drop tower test fixture

A vertically sliding platform also known as a drop tower test fixture is shown in Fig 6. ATDs can be seated and the platform, including the seat and ATD, dropped from a suitable height to achieve any desired Δv over the duration T . The target pulse can be achieved by controlling the energy absorption characteristics of the floor on which the platform is dropped upon. Alternatively, a base excitation can be provided to the sliding platform in the upward vertical direction to achieve any given pulse if the fixture is so equipped (Also known as vertical sled). These two scenarios are completely equivalent in the occupant response behavior for the same given pulse.

Occupant injuries recorded from both these approaches were compared against those measured during physical tests. The resulting comparison showed no significant differences between the two approaches. Therefore the ensuing parametric modeling and simulation (M&S) study, involving a

large number of simulations, was conducted on the latter multibody-based MADYMO® model since the run times for the latter are significantly lower than that of the FE-based model.

Parametric Study

A parametric study was conducted by varying the peak acceleration from 10g-1200g, and duration of the pulse from 2.5ms to 60ms (a total of thirteen distinct duration levels) such that Δv is varied to a maximum value of about 15 m/s. The blast pulses with the minimum and maximum amplitudes from these thirteen duration levels are shown in Fig 7. In addition to a rigid seat without an energy-absorbing (EA) mine blast feature, two other generic EA blast mine seats of different ratings (EA1, EA2) were also used in the study (Fig 8). As may be observed from the figure, both EA seats have the same amount of stroke, but EA2 is softer in that it strokes at a lower limiting force level than EA1.

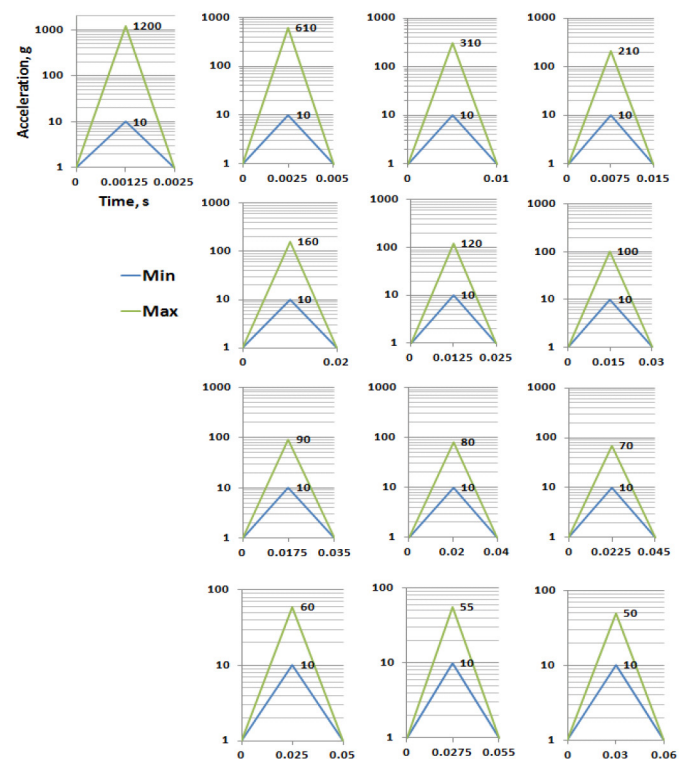


Fig 7. Blast pulses with minimum and maximum amplitude for the thirteen duration levels considered in this study.

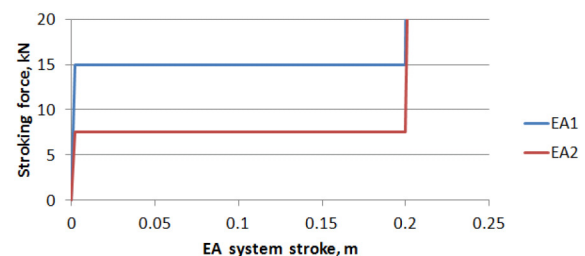


Fig 8. Two generic seat EA systems characteristics considered. Baseline EA (EA1) and Softer EA (EA2)

A total of ten different upper body injuries were recorded and monitored, namely:

- (1,2,3) Peak, 2ms clip and HIC_{15} criterion of the head resultant acceleration,
- (4) N_{ij} criterion for the neck injury,
- (5,6) 3ms and 7ms clips of chest resultant acceleration,
- (7) 7ms clip of pelvic vertical acceleration,
- (8,9) Peak and 30ms clips of lumbar spine compression, and
- (10) Pelvic vertical Dynamic Response Index (DRI)[12].

The sample size for each of the three seating variants consisted of 230 MADYMO® simulations, for a total of 690 data points. For each simulation, the ten occupant injuries are plotted and assessed using the post processing tool Hypergraph® as shown in Fig 9. In the next section, each of these ten injury responses are plotted against three different blast loading parameters, grouping them by the pulse duration T , to look for trends (Fig. A2).

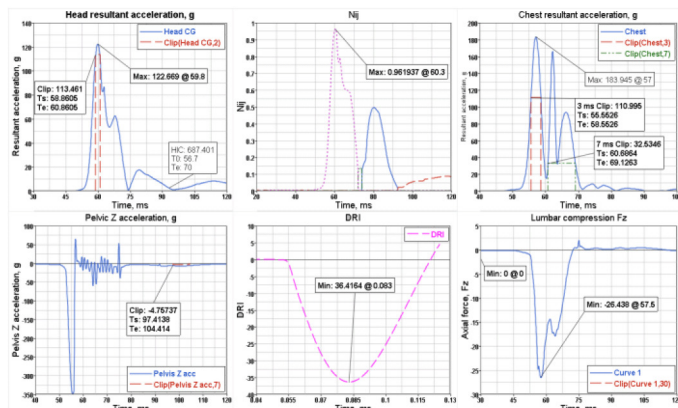


Fig 9. Recording occupant injury metrics

Occupant Injury Responses

Figs A1 shows ten occupant injuries, plotted against the change in velocity, Δv , for the three seat types. The first column of plots shows the ten occupant injuries for the rigid seat, plotted against Δv . The second and third columns of plots are the same injuries for the seats EA1 and EA2, respectively.

In each of the 30 plots in Fig A1-a & b, several curves can be seen. Each of these curves corresponds to a constant value of T , the duration of the blast pulse. In essence, they are the same as iso- T curves.

Findings

A detailed regression study was conducted to see if there was a single blast loading parameter which could be used to adequately characterize occupant injuries. Three blast loading

descriptors proposed in the literature [12, 13, 14], viz., Δv , G_{eff} and Specific Power (SP) were evaluated for this purpose. Figure A2 shows occupant injuries HIC_{15ms} (Fig. A2-a) and DRI (Fig. A2-b) plotted against these three blast loading parameters for the three different seat designs considered in this study. It may be observed from Fig A2 that the injury responses are much more bunched together when plotted against Δv , as opposed to the other two blast loading parameters, thereby indicating a higher potential for Δv to be the single indicator for occupant injury characterization. This trend to bunch together is even more pronounced in smaller intervals of T , that is, in 10 ms groupings such as 0-10, 10-20, 20-30, etc. It must also be mentioned here that the iso- T curves, for all three load descriptors, tend to bunch together much better for larger values of pulse duration T (>30 ms), but these durations are not typical of underbody blasts but more representative of standard automotive crash events. These observations were also validated by the rigorous regression study, the key finding being that Δv is the best single indicator for estimating injury criteria, for typical blast pulse duration ranges (0-20 ms), independent of seat type.

REDUCED ORDER MODELS (ROM) / INJURY LOOK-UP TABLE

Three different Reduced Order Modeling approaches to construct injury look-up tables with increasing levels of fidelity and thereby accuracy are described below.

Approach #1 (Single Parameter)

Using the linear/quadratic regression equations resulting from this parametric study, occupant injuries for any triangular-shaped pulse can be easily computed. As an example, Figure 10 shows one such occupant injury, viz., Head acceleration 2ms clip vs. Δv .

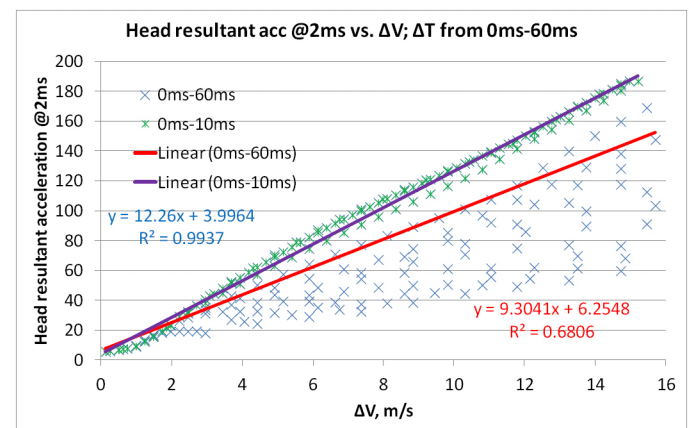


Fig 10. Head resultant acceleration vs. Δv for two duration ranges

Head acceleration (2ms clip) now can simply be calculated by using the linear regression equations from the curve above. For the entire range of T , i.e., $0 \leq T \leq 60ms$,