Title: *Utilizing Vehicle Response Data from Under-body Blast Tests*

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Vehicle mounted instrumentation data recorded during under-body blast events is being better utilized to provide valuable insight into vehicle response thus aiding in better vehicle survivability recommendations and improvements. Recently there has been an emphasis on designing ground vehicles according to occupant response and injury metrics without large consideration to vehicle response metrics. The data recorded through vehicle mounted instrumentation such as accelerometers supplements occupant response data and greatly enhances an understanding of total and intermediate system response. This paper will explain how data recorded at the floor helps with evaluating vehicle floor designs, how data recorded at the seats facilitates a fuller assessment of seat performance and protection, and how rigid body data can be extracted from accelerometer data to assess global vehicle motion and response. The expanded use of this data has advanced the understanding of vehicle response and helped to improve vehicle survivability.

BACKGROUND

Protecting crew occupants has always been the primary concern for vehicle survivability design. The historical approach to maximizing survivability was to protect the occupants by considering what conventional threat impacts the vehicle, and in which location. For instance, the frontal arc of a tank has traditionally been designed to defeat incoming tank gun fire. The recent increase in large unconventional under-body blast attacks by a terrorist enemy shows that any area of the vehicle can be targeted. These attacks have led to different type of crew injuries necessitating the development of metrics in Live-Fire to understand how to better protect occupants from these new threats.

The rise of under-body blast attacks has expanded the interest in and quantity of under-body blast tests performed on vehicles with specific interest on crew survivability. The emphasis on crew survivability has enhanced the implementation of instrumentation greatly. More advanced under-body blast test mannequins were

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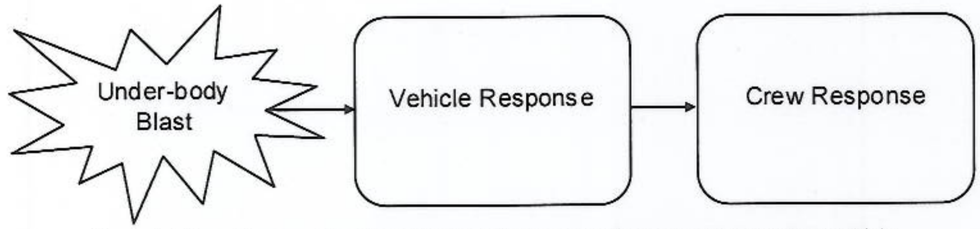

Figure 1. Flow diagram of system response during an under-body blast event to vehicle

implemented in tests and a greater amount of vehicle mounted instrumentation was used. The vehicle mounted instrumentation includes accelerometers, strain gauges, blast over-pressure gauges, break wires, and more. The test mannequins were made to record more and more injury mechanisms in an attempt to best capture crew response. However it should be noted that the interest in crew survivability is inherently linked to vehicle response and survivability as well.

Crew injury data recorded by the test mannequins provide substantial insight into occupant response during under-body blast test events. However, it is necessary to link this crew injury data to vehicle response so that the whole system, including the vehicle itself, can be best designed for survivability. The simple flow diagram of a blast event in Figure 1 illustrates that a comprehension of vehicle response along with crew response is essential to an understanding the entire system response. Most under-body blast tests were typically viewed to produce either a pass or fail result based solely on the presence of occupant injury. This simplified approach with binary results dramatically underutilizes the wealth of data that is collected during these test events. Therefore the goal became to understand and utilize the vehicle response data, independently and in conjunction with the crew response data. In this way the entire system response can be best understood in order to improve vehicle and crew survivability.

VEHICLE RESPONSE DATA

The vehicle mounted instrumentation data most often used to understand vehicle response is the accelerometer data. Accelerometers produce acceleration versus time at the position at which they are mounted. For the case of test events against ground vehicles the accelerometers are most often mounted throughout the vehicle at the floor and seat. There are additional accelerometers mounted to other areas of interest such as the roof, hull interior, side wall, etc, depending on the specific vehicle design. First, an understanding of the output from the accelerometers during the under-body blast events is necessary to use the data in conjunction with the crew injury data.

Correcting the accelerometer data

It was quickly noticed that the acceleration data that was output during under-body blast events needed some post-processing. This is mostly due to the observation that the first and second integrals of the acceleration data (velocity and displacement respectively) did not match what physically occurred during the test. Specifically, there seemed to be some sort of offset present in the acceleration data which became more apparent in its integrations. Additionally, spurious spikes in the acceleration data were noticed. These anomalies are attributed to the accelerometers being exposed to such a severe shock environment during these under-body blast tests. This environment can cause stretching of wires, glue failure, or other damage mechanisms that lead to data in need of post-processing. A series of post-processing techniques were employed to correct the data into a form that could then be confidently used for subsequent analyses. The general post-processing steps consist of first performing a low pass filter based on an inspection of the frequency spectrum to remove some of the spurious spikes. Next, the data is integrated to produce velocity and displacement. A trend is then removed in the integrated data to account for the offset. Once these two general steps are performed (filtering and trend removal) the data is examined to ensure that it appears reasonable. This corrected data is the data set used for all following analyses.

The accelerometer data

In addition to providing the acceleration versus time, the data can be integrated to yield velocity and displacement versus time. These three data sets aid in understanding vehicle response in different ways. The acceleration is the direct output of the gauge and a Fourier transform can be performed to produce the frequency response at the gauge position. Integrating the acceleration to get velocity versus time is a sort of filter of the acceleration data and is a more reliable and consistent means of understanding the local response. The displacement data shows the global motion of the gauge from the perspective of standing outside the vehicle looking at the gauge. An example of a typical corrected acceleration, velocity, displacement, and frequency spectrum data set is shown below in Figure 2. Each data set can be and is used to characterize vehicle response.

ANALYZING THE DATA

The accelerometer data has been analyzed in various ways to provide insight

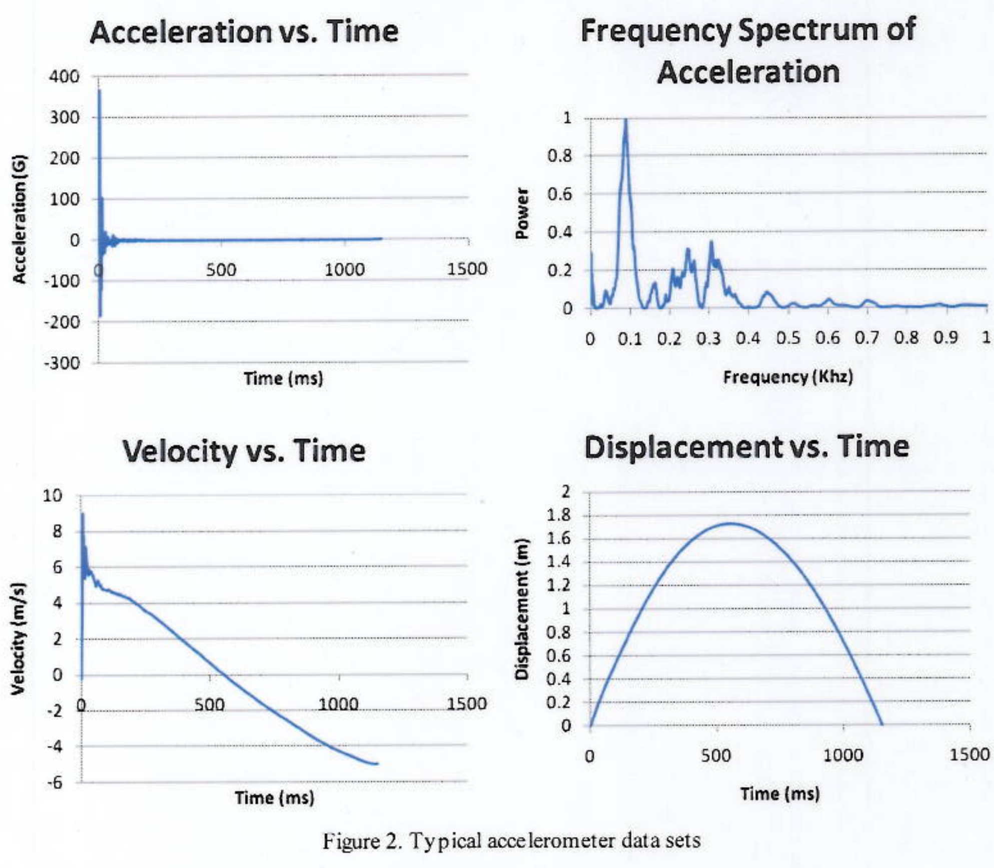

Figure 2. Typical accelerometer data sets

into what is going on at specific areas of the vehicle. Two areas of interest are the vehicle floor and the crew seats, where accelerometers have been mounted to offer data that can be analyzed to characterize the response at those positions.

Floor response

The accelerometer data from gauges mounted to the floor have been best analyzed in the form of its first integral, velocity, to characterize floor response. This was specifically identified during an analysis to link floor accelerometer data to the injuries recorded by the test mannequins. This analysis utilized a past study of floor and leg interaction through a mathematical dynamic model. The model results showed that there was a link between floor velocity and lower tibia compressive force. This floor and tibia link from the model was blended with data from under-body blast tests to create a hybrid model with an empirical link. This link utilized floor velocity data characterized by its Δv and duration values. These parameters are based on the half-sine wave velocity curve which was used as model input. Therefore the Δv is the maximum velocity of the initial peak in the velocity trace and the duration term is the duration of that peak. An example floor data set is shown in Figure 3 with the Δv and duration term identified.

The hybrid model identifies an expected tibia compressive force based on modeling and test results given a certain floor velocity. This link is based on the assumption that the floor gauge is in proximity to the lower leg that is positioned normal to the floor. The empirical data used in conjunction with the model results has crew member's feet placed within about six inches of the accelerometer and legs as straight and normal to the floor as possible. Some variability is expected due to differences in leg-to-gauge distance and the exact leg-to-floor angle. Over two hundred empirical data points were used with the model results to link floor response and leg injury. The model was run for cases with feet flat on the floor and legs straight.

The link between the floor velocity and the lower tibia compressive force provides a means to analyze floor data with respect to injury. As previously stated, most under-body test events are conducted with specific interest in crew injury, so linking floor data with crew injury enables the floor data to be included in understanding vehicle response.

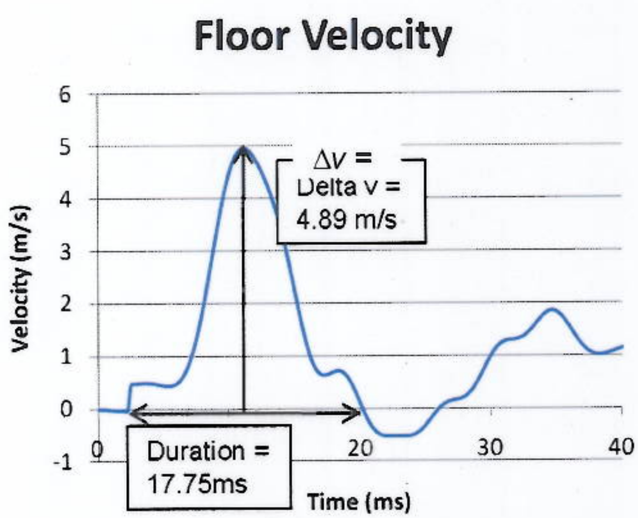

Figure 3. Example floor velocity with Δv and duration identified

Seat response

The seat accelerometer data has been most commonly used in the form of velocity and displacement to characterize the seat response with respect to crew injury. The peak vertical rigid body displacement measured at a seat accelerometer has shown to correlate well to the core injuries (pelvis and upper body) measured by the test mannequin. The core injury chosen to correlate to seat data was the vertical dynamic response index (DRI-z) because it was the most common core injury during the series of under-body tests. DRI-z is a metric relating to lumbar spine response during a dynamic event derived from a mass-spring damper system subjected to vertical forces. Over four hundred crew DRI-z, peak seat displacement data points were plotted and a linear fit was found. A plot of the data along with the line of best fit is shown in Figure 4. Additionally, seat velocity data has been used to show what is occurring on a local level at the seat. For example, accelerometers have been positioned at a seat mount and seat pan to represent input and output to the seat. Comparing the velocity traces of the input and output can aid in understanding the effects of the seat mount and any energy attenuation system. Figure 5 shows a seat input and output velocity trace.

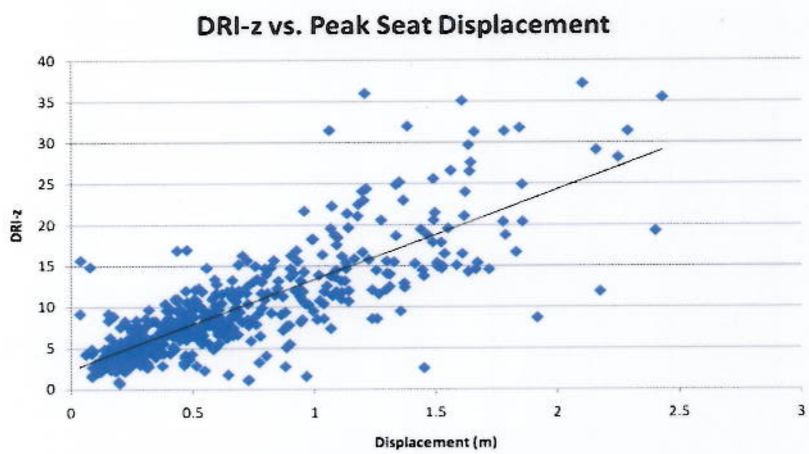

Figure 4. DRI-z versus seat displacement

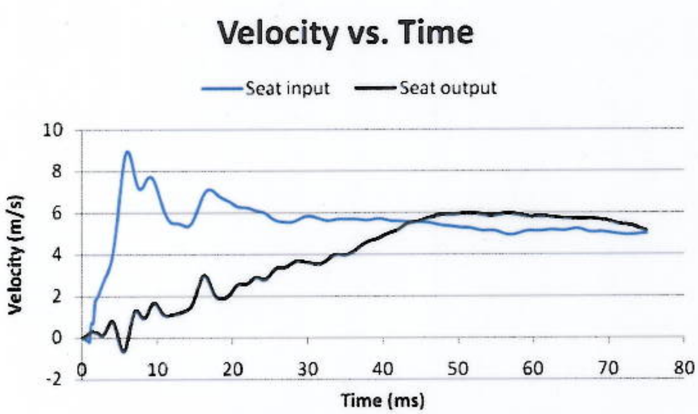

Figure 5. Velocity versus time of seat input and output

ANALYSIS EXAMPLES

The use of floor and seat data with respect to crew injury has allowed for a number of analyses that provide insight into vehicle response as it pertains to crew injury.

Assessing vehicle modifications

Some vehicle design modifications are made with the purpose of improving crew protection from under-body blast events. The vehicle-mounted instrumentation data is ideal for evaluating the performance of these vehicle modifications. For example, a specially designed mat was added to the floor of a series of vehicles. This floor mat was designed to mitigate forces transmitted to occupants' legs during under-body blast events. The general methodology behind analyzing the mat performance is shown in Figure 6. The floor accelerometer data was used to find the expectation of the compressive force from feet placed on the floor. The link between floor velocity and lower tibia compressive force was used for data at each crew position and the expected value was compared against the actual value. The link between the floor velocity and tibia compressive force used in this analysis was made by calculating the surface from a least squares fit of the empirical floor Δv, duration, and tibia compressive force data; this is shown in Figure 7. This allowed for an estimation of the lower tibia compressive force based on the measured floor Δv and duration. The actual tibia compressive force for crew members with feet on the mat was compared to the tibia compressive force estimated for crew members with their feet on the floor. This difference was the mat's force mitigation performance. Utilizing the under-body blast data from these test events allowed for the mat to be evaluated.

Another example of utilizing the under-body blast data for vehicle modification assessments is the analysis of an independent suspension add-on to certain vehicles. In this case a series of solid axle suspension events had previously occurred and could be directly compared to the independent suspension events. A variety of vehicle data metrics were examined and it was determined that the floor velocity and vehicle rigid body motion, along with crew core injuries, could be used to help assess the independent suspension's impact on survivability. However, for some events crew positioning was also changed between the solid and independent suspension events such that crew members did not place their feet on the floor. Other engineering changes were made to the vehicles including a floor mat and new seats which would affect crew injuries. An analysis of the independent suspension's affects, based solely on comparing crew injury results, was determined to be extremely difficult because of the engineering changes and amount of variables added to the system. Therefore, the vehicle mounted data was used to eliminate a number of variables and provide enough information to assess the independent suspension. Since leg injury results would vary according to foot placement, the

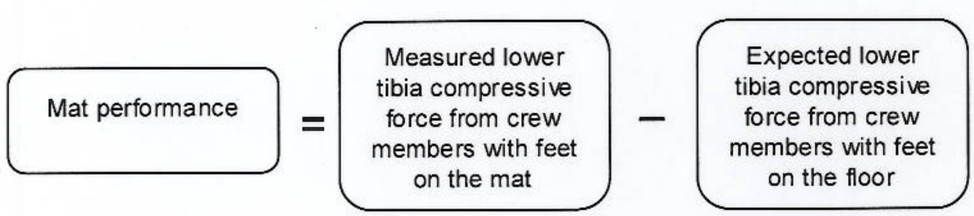

Figure 6. Mat performance methodology diagram

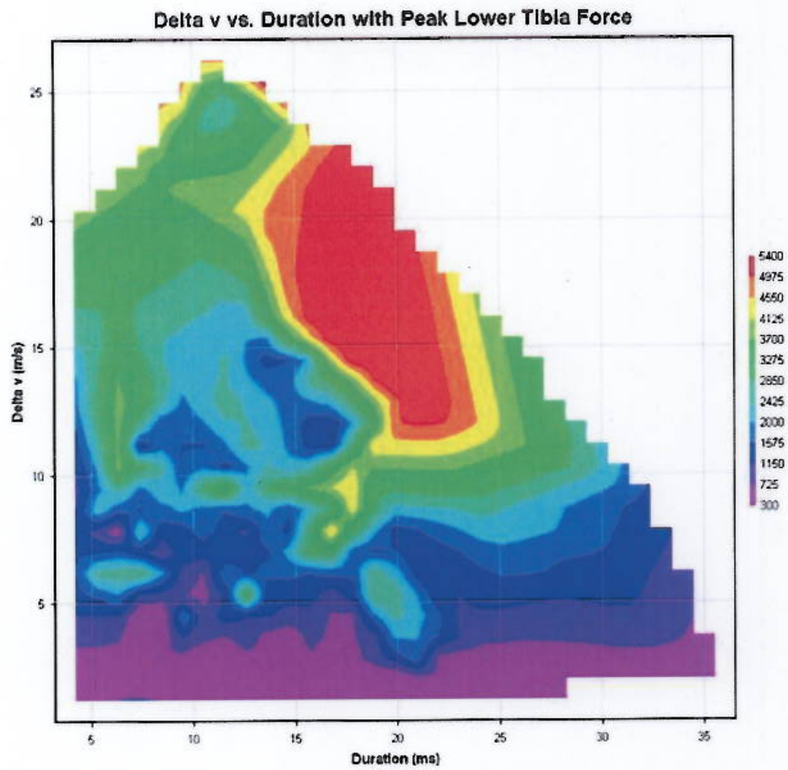

Figure 7. Empirical fit of floor Δv, duration and lower tibia compressive force

floor accelerometer data was utilized to uniformly compare floor severity. Also, since crew core injuries were affected by seat differences, the vehicle rigid-body motion could be compared between solid and independent suspension events to assess its effects. Overall, data from twelve event pairs were analyzed and an assessment of independent suspension effects to survivability could be made even with other changes present to the vehicle.

Supplementing test event reports

In addition to performing an analysis of under-body blast data for stand-alone studies, these techniques have been used to supplement particular test event reports. For example under-body blast data has been used to show the amount and timing of floor deflections. The floor deflection data has been used to show that the floor struck a component of the vehicle located a certain distance above the floor. For one particular instance this data aided in verifying that an elevated leg injury observed in the crew data was due to the floor striking the stirrup on which the leg was resting. A graph of this data is shown in Figure 8. In other cases the floor deflection data has been used to show the height that components such as seats and stirrups need to be placed above the floor in order to avoid contact from the floor during an under-body blast event.

Expensive test mannequins are not used in some test events conducted with fragmenting artillery rounds due to the risk of losing the equipment from fragment damage. In these situations the floor data can be used to provide an estimate of tibia injury from the blast effects of the round in lieu of a test mannequin. As before, the link between floor velocity and tibia compressive force is employed to create the estimate of tibia injury. For these cases the under-body blast data is extremely

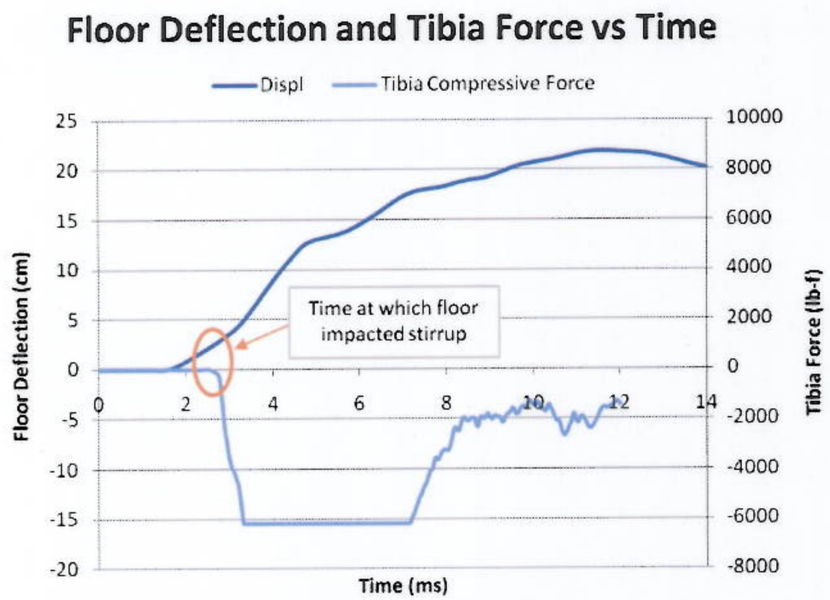

Figure 8. Floor deflection and tibia force versus time

useful because it provides the only insight into potential injury from the blast and shock effects.

BENEFITS OF UTILIZING UNDER-BODY BLAST DATA

The developing use of vehicle mounted under-body blast data is aiding in support and implementation of improved survivability designs. This is due to a fuller understanding of vehicle response as it affects the occupants. Utilization of under-body blast data makes it possible to make quantitative vehicle design recommendations to improve occupant survivability. Rule-of-thumb vehicle response criteria have been offered to vehicle designers to create and test their vehicles to derived vehicle response metrics. These metrics include vehicle jump height and floor velocity. The rule-of-thumb values allow vehicle vendors to test a vehicle without costly test mannequins and specifically address their area of expertise, vehicle design, with a measure of how it affects crew survivability. Additionally, the data serves to create expectations of occupant injury in limited instrumentation situations where test mannequins cannot be used because of risk of losing costly test assets. The analysis of under-body blast data also allows for vehicle data to be used, in conjunction with crew injury results where possible, to assess vehicle design changes. Finally, the promoted use of vehicle response data is used, in concert with crew injury data, to validate model results. Overall, the analysis of vehicle data from under-body blast events has advanced the understanding of the vehicle response, thus aiding in development of improved and more survivable vehicles.