Analysis of Spinal Compression and Energy-Absorbing Seats in Blast Environments

James Eridon
General Dynamics Land Systems, Sterling Heights, Michigan

Summary

Combat vehicle designers have made great progress in improving crew survivability against large blast mines and improvised explosive devices. Current vehicles are very resistant to hull failure from large blasts, protecting the crew from overpressure and behind armor debris. However, the crew is still vulnerable to shock injuries arising from the blast and its after-effects. One of these injury modes is spinal compression resulting from the shock loading of the crew seat. This can be ameliorated by installing energy-absorbing seats which reduce the intensity of the spinal loading, while spreading it out over a longer time.

The key question associated with energy-absorbing seats has to do with the effect of various factors associated with the design on spinal compression and injury. These include the stiffness and stroking distance of the seat's energy absorption mechanism, the size of the blast, the vehicle shape and mass, and the weight of the seat occupant. All of these affect the spinal compression, as measured by the Dynamic Response Index. This paper presents a simple analytical model which ties together all of these variables, showing the effect of different energy-absorbing designs on crew survivability over a range of blast conditions. The analysis shows that the most important factor in determining the capability of the system to prevent injury is the stroking distance available to the energy-absorption mechanism. In addition, the analysis shows the limits of performance available to any seating system, and also how to optimize the seat design to produce minimum spinal compression for any given set of design parameters.

Introduction

One of the significant sources of crew injuries due to underbelly mine blasts and improvised explosive devices (IEDs) is the vertical shock delivered to the spine. This produces compression of the inter-laminar disks and can result in severe and permanent injuries. One way to mitigate this damage is to incorporate energy-absorbing seats in the vehicle design. These reduce the shock loading on the spine by spreading the impulse out over a longer time, during which the seat itself strokes downward relative to the vehicle mounting location. By allowing the seat to absorb shock in this manner, the overall spinal compression, and the resulting likelihood of injury, can be greatly reduced.

The key questions associated with the design of such a shock-absorbing seat system have to do with the stiffness of the shock absorbing element, the length of the stroke needed to mitigate the shock, the maximum intensity of the blast shock that can be reasonably mitigated, and the effect of various random factors (for example, variation in crew weight, or initial vehicle velocity) on the performance of the shock mitigation system. For example, typical requirements call for the mitigation of shock to all crew occupants ranging from the 5th percentile female (weighing about 50 kg) to the 95th percentile male (weighing about 98 kg). It is challenging to design a shock absorbing system that functions over such a wide range of loading.

This paper will address these questions by performing a straightforward analysis of the equations of motion of the crewman in a shock-absorbing seat subjected to a blast load, coupled with the equation of compression of the human spine. The latter equation comes from the definition of the Dynamic Response Index (DRI), which describes the human spine as a simple lumped spring-damper system. Both of these equations have the same form – second-order differential equations with constant coefficients. As such, both are subject to exact analytical solutions. By solving these equations, we can estimate the effects of the various design parameters and random factors on spinal compression and probability of injury. In addition, we can also look at the performance of "non-ideal" shock absorbing systems. For example, we can estimate what happens when the seat system "bottoms out" during an overmatch event, using up the entire available stroke and finally bouncing off the floor of the vehicle.

Motion of the Crewman

We begin by examining the motion of the crewman in an energy absorbing seat following a blast event. The figure below shows the key factors we need to consider.

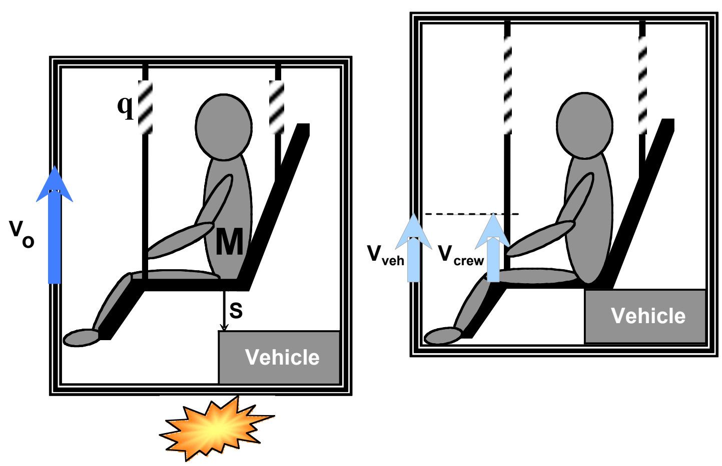

Figure 1. Key factors in the motion of the crewman during a blast event.

Before the blast, the crewman (mass M) is sitting at rest in an energy-absorbing seat that is attached to the vehicle in a shock-isolated mounting (for example, attached to the ceiling). This prevents the transmission of any direct shock loads to the crewman. The blast lifts the entire vehicle (including the seat mount) off the ground at an initial velocity V_o. The crewman does not feel this initial load, because his seat has a shock-absorbing element which only transmits a force proportional to the difference between the seat velocity and the vehicle velocity. Initially, this force is equal to $q \cdot V_o$, where q is the stiffness of the shock absorbing element (energy-absorbing element) in the seat. This force is less than that needed to accelerate the crewman to the liftoff velocity of the vehicle. As a consequence, as the vehicle moves upward at velocity V_o, the crewman moves upward at a much lower velocity, V_{crew}. Viewed from inside the vehicle, this means that the crewman is actually moving downward relative to the vehicle – toward the vehicle floor. He will continue to move downward until either he strikes the floor of the vehicle, or his velocity matches that of the vehicle. The distance he has available before striking the floor is called the stroke (S). Ideally, the seat stiffness (q) will be set such that the entire available stroke (S) is used to cushion the blast impulse (V_o) on a crewman of mass M. In practice, any number of energy-absorption mechanisms are available, including those which use crushable metal tubes, hydraulic shock absorbers, bent metal strips, extrudable metallic cups, or any other mechanism that performs plastic work in a manner proportional to the distance of travel.

For the purposes of this analysis, we will make a few simplifying assumptions regarding the seat system. First, as described earlier, we'll assume that the seats are mounted to the vehicle in such a way as to eliminate any direct shock paths to the crewman. This allows us to consider only the gross vehicle rigid-body motion as the input to the crewman. In general, this means that the seat mounts should be located away from the blast site, at a relatively stiff location not subject to high deflections - for example, on the ceiling of the vehicle, near a vertical sidewall or bulkhead.

Second, we'll ignore any possible spring element in the seat. In general, all seats have some degree of springiness to them, and it is not difficult to solve the equations with the addition of a spring term. However, this does not add to the general understanding of the problem associated with seat stroke and shock absorption, and in fact may obscure some of the important points.

Finally, as mentioned above, we'll assume that the human spine can be reasonably well-modeled as a lumped spring-damper system as described by the Dynamic Response Index equation. Further, we'll assume that the crewman is firmly belted into the seat, so that he and the seat move as one. This eliminates the consideration of any "padding" available in the human body itself, and makes this analysis somewhat conservative (that is, the performance of any seat system designed using these equations will be somewhat better than estimated).

With these simplifying assumptions, we can write the equations of motion for the vehicle and the crewman in an energy-absorbing seat subjected to a blast load that lifts the entire vehicle off the ground at an initial velocity V_o. We'll describe the position of the vehicle (height of the vehicle off the ground) by H_V, and the position of the crewman (height of the crewman above his initial position) by H_C. Therefore, the stroke of the seat at any given moment is given by the difference between the two, $S(t) = H_V – H_C$, and the force on the crewman is proportional to the difference in velocity between the two, $q \cdot [dH_V/dt – dH_C/dt]$.

Vehicle Equation of Motion: $H_V(t) = V_o \cdot t - \dfrac{g \cdot t^2}{2}$ (1)

Crewman Equation of Motion: $M \cdot \dfrac{d^2 H_C}{dt^2} = -g \cdot M - q \cdot \left[\dfrac{dH_C}{dt} - \dfrac{dH_V}{dt} \right]$ (2)

In these equations, g is the acceleration of gravity (9.806 m/s_). (Again, assumptions about the rigid-body motion of the vehicle to allow us to write the first equation.) These two equations can be solved simultaneously in order to determine the motion of the crewman in the seat during the blast event. The solutions are simply:

Crewman Motion: $H_C(t) = \left(\dfrac{M \cdot V_o}{q} \right) \cdot \left[e^{-qt/M} - 1 \right] + V_o \cdot t - \dfrac{g \cdot t^2}{2}$ (3)

Seat Stroke: $S(t) = \left(\dfrac{M \cdot V_o}{q} \right) \cdot \left[e^{-qt/M} - 1 \right]$ (4)

The following figures show the results for a simple case. The figure on the left shows the velocity of the vehicle and the velocity of crewman during an event in which the initial impulse is 7 m/s. The crewman weighs 100 kg, and the value of q is 3017.3 kg/s. It shows that the crewman's velocity gradually approaches that of the vehicle, while the vehicle itself is slowing down slightly due to gravity. Because the solution is an exponential, the crew velocity never quite reaches the vehicle velocity, but after 120 msec they are very close. The figure on the right shows the position of the vehicle, the position of the crewman, and the stroke for the same parameters. In this figure we can see the stroke of the seat gradually approaching the maximum value of about 232 mm, at which point the vehicle and crew position lines are nearly parallel.

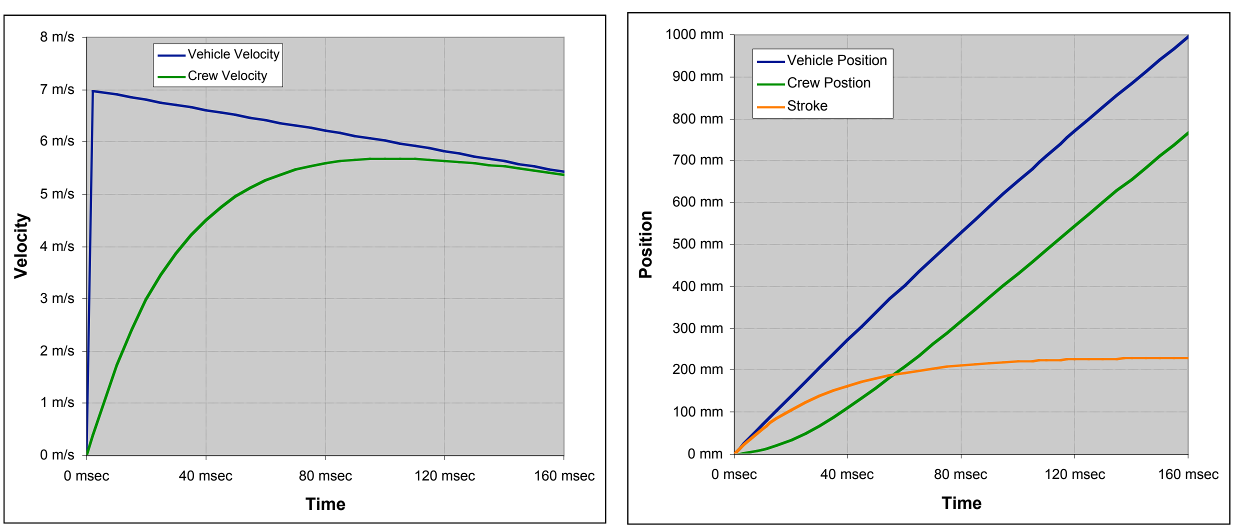

Figure 2. Vehicle and crew velocity, positions and seat stroke for a blast event.

Spinal Compression and the Dynamic Response Index (DRI)

The Dynamic Response Index DRI is a measure of spinal compression in response to a shock event. It is calculated as the solution to a simple spring-damper equation that models the human spine. In this equation, δ is the compression of the spine, while d^2z/dt^2 is the shock load.

$$\frac{d^2\delta}{dt^2} + 2\varsigma\omega\frac{d\delta}{dt} + \omega^2\delta = \frac{d^2z}{dt^2}, \text{where } \varsigma = 0.224, \text{ and } \omega = 52.90 \text{ radians/sec} \tag{5}$$

The DRI is proportional to the maximum value of spinal compression δ, DRI = $\delta_{max}\cdot\omega^2/g$. NATO standards indicate that a DRI of 17.7 equates to a 10% chance of spinal injury, while a DRI of 15 is often used as a design goal.

The shock load to the spine is described by the term on the right-hand side of the equation, d^2z/dt^2. We already have an expression for this term as the motion of an energy-absorbing seat in response to a shock load. As a consequence, we can write a single equation for spinal compression and the motion of the seat, and solve it analytically to find the spinal compression as a function of time:

$$\frac{d^2\delta}{dt^2} + 2\varsigma\omega\frac{d\delta}{dt} + \omega^2\delta = \frac{d^2H_c}{dt^2} = \left(\frac{qV_o}{M}\right)\cdot e^{-qt/M} - g \tag{6}$$

$$\delta(t) = C_1 \cdot e^{-\varsigma\omega t}\cdot\cos\left(\frac{t}{\tau}\right) + C_2\cdot e^{-\varsigma\omega t}\cdot\sin\left(\frac{t}{\tau}\right) + \frac{\left(\frac{qV_o}{M}\right)\cdot e^{-qt/M}}{\left[\left(\frac{q}{M}\right)^2 - 2\left(\frac{q}{M}\right)\varsigma\omega + \omega^2\right]} - \frac{g}{\omega^2} \tag{7a}$$

where $\tau = \frac{1}{\omega\cdot\sqrt{1-\varsigma^2}} = 19.4\,\text{msec}$ and: (7b)

$$C_1 = \frac{g}{\omega^2} - \frac{\left(\frac{qV_o}{M}\right)}{\left[\left(\frac{q}{M}\right)^2 - 2\left(\frac{q}{M}\right)\varsigma\omega + \omega^2\right]}, \quad C_2 = \frac{\left(\frac{qV_o\tau}{M}\right)\cdot\left(\frac{q}{M} - \varsigma\omega\right)}{\left[\left(\frac{q}{M}\right)^2 - 2\left(\frac{q}{M}\right)\varsigma\omega + \omega^2\right]} + \frac{g\varsigma\tau}{\omega} \tag{7c}$$

The values of the constants C_1 and C_2 depend on the initial conditions of the seat. The expressions given above correspond to the case where the seat is initially at rest at the equilibrium position ($H_C(0) = dH_C(0)/dt = 0$). The value of τ (19.4 msec) is a characteristic of the DRI model of the human spine.

What this means in terms of spinal injury can be seen by examining the figure below. This shows the spinal compression for the case of a 7 m/s shock load in both a standard rigid seat (bench seat) and an energy-absorbing seat (damped seat).

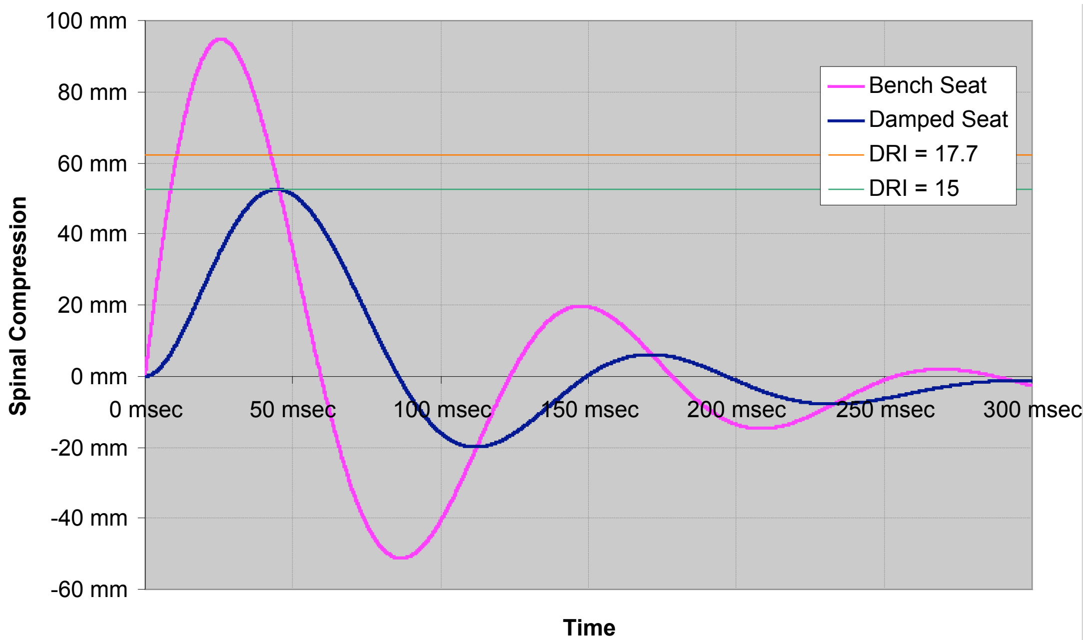

Figure 3. Spinal compression in a shock-absorbing versus a rigid seat.

The figure shows that the 7 m/s shock load is sufficient to produce over 90 mm of spinal compression, corresponding to a DRI of about 27.7, well in excess of the critical value of 17.7. However, by including a seat with a shock-absorbing mechanism with a stiffness (q) of 3017.3 kg/s, the resulting spinal compression of a 100 kg crewman would be reduced to just over 50 mm, corresponding to a DRI of only 15. Again, in order to obtain this performance, the seat would need about 232 mm of stroke to avoid bottoming out against the vehicle floor.

Key Survivability Relations (Ideally Damped Seat)

The key elements of the model include the following four parameters:

- Occupant Mass M
- Stroke Length S
- Damping Force q
- Blast Impulse V_o

The equations dictate some relations between these parameters. For example, we can write the following relation that describes how the seat stroke changes with variations in occupant mass, damping force, or blast impulse. Again, this holds for an ideally damped seat (in which there is sufficient stroke to avoid bottoming out seat).

$$S = \frac{M \cdot V_o}{q} \tag{8}$$

This simply says that the stroke increases linearly with occupant mass or blast impulse, and decreases inversely with the stiffness of the energy-absorbing mechanism. What this means is that in order to maintain the same stroke for different sized crewman, the stiffness has to be adjusted in such a way as to keep the value of M/q constant. This will provide the same shock-absorbing quality, and the same spinal compression and DRI, for different seat occupants.

Using the solutions above, we can also calculate the relationship between the seat stroke required to achieve a given value of DRI as a function of the initial impulse V_o (which relates to the size of the blast). For example, if we desire a DRI of 15, and want an ideal solution in which the seat never bottoms out, the figure below shows this relationship. Again, this is subject to the assumptions discussed earlier (impulsive load, no spring in the seat or the body, rigid body motion, etc.). The actual DRI experienced by a soldier (or an ATD) would be somewhat lower.

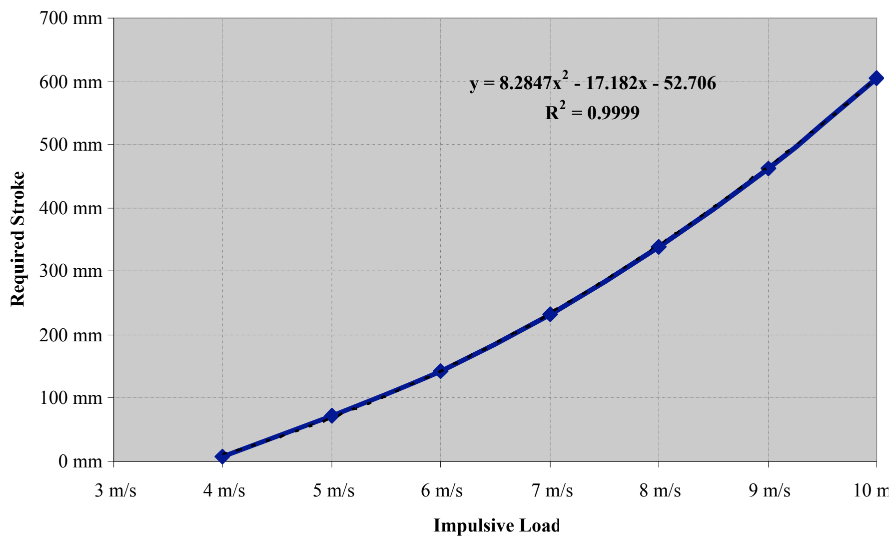

Figure 4. Required ideal stroke as a function of load for a limiting DRI=15.

Non-Ideal Seat Stroke and Damping

The previous analysis considered the case where the seating system was designed with sufficient stroke to ensure that the seat never bottomed out against the floor of the vehicle. This is the easiest situation to analyze, and clearly the preferred mode of operation. However, combat vehicles are notoriously cramped and may not always have space available to allow for maximum seat stroke. Also, equation (8) above shows that a heavier seat occupant, or an overmatching threat, could easily result in a situation where the seat uses all the available stroke and still bumps against the floor of the vehicle. The question then is, if the energy-absorbing mechanism works as designed but the seat still bumps against the floor, how much more spinal compression will the occupant experience?

This particular problem is not subject to the simple analysis used previously, owing to the fact that the “bump” is essentially a delta-function load introduced at a variable time following the event. However, it is still possible to model the event numerically and identify several important points. Foremost among them is the fact that the maximum spinal compression does not necessarily increase when the seat bottoms out. However, this will result in an increase in the maximum instantaneous force on the spine, which could still lead to injury.

The figures below show the result of a simulation of a blast event similar to that modeled previously – 7 m/s impulse, in a seat with 232 mm of stroke, designed to provide a DRI of 15 for a 100 kg occupant (q = 3017 kg/s). In this case, however, the occupant weighs 130 kg. The figure on the left shows the vehicle velocity, the seat (crewman) velocity, and the spinal compression rate. The figure on the right shows the actual spinal compression as a function of time.

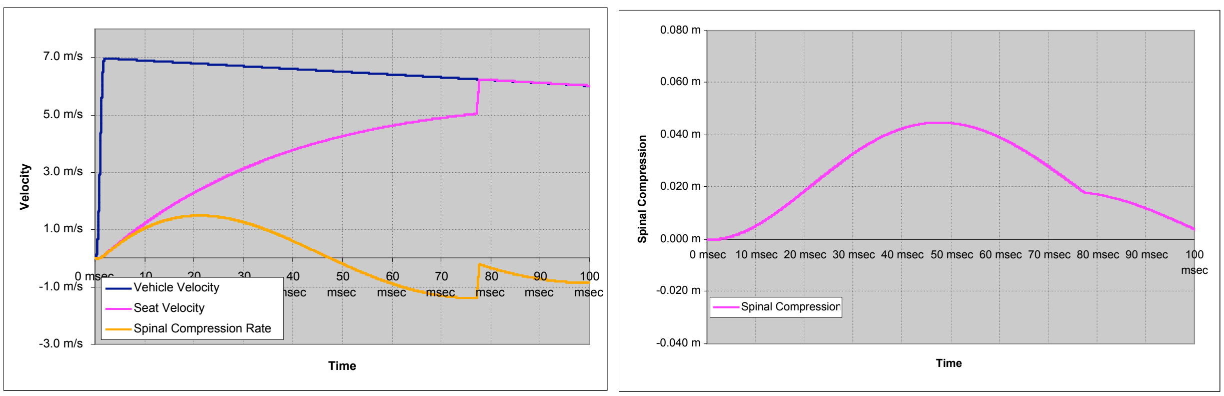

Figure 5. Spinal compression for a heavy seat occupant during a blast event.

The figures clearly show the seat bottoming out around 77 msec into the event. At that point, the spinal compression curves show discontinuities as the shock propagates up into the spine. However, this is a fairly minor event. The difference between the floor velocity and the vehicle velocity at impact is only about 1.6 m/s. In addition, the spine is actually rebounding at that point. That is, the spine has already reached full compression, and is now bouncing back (the spinal compression rate is negative). This small shock is not enough to change that, so the maximum spinal compression in this case is no larger than it would have been had the seat not bottomed out at all.

Effects of Variation in Occupant Weight

The figure below shows the effect of occupant mass variation in a seat with finite stroke. Again, the design parameters are as before (7 m/s, 100 kg, 232 mm, DRI=15). In this figure, the brown dotted line indicates the impulsive DRI limit – the value of DRI that would result if there were no energy absorbing elements in the seat at all. The blue line indicates DRI as a function of initial impulse for the 100 kg seat occupant. Again, the DRI value reaches 15 at an initial impulse of 7 m/s, at which point the seat uses the entire 232 mm of stroke. The pink line shows the DRI for a lighter-weight (75 kg) seat occupant, one who does not use the entire stroke and therefore feels a rougher ride. The red line shows the DRI for a heavier (125 kg) seat occupant, who uses more than the entire stroke and actually bottoms out at 7 m/s.

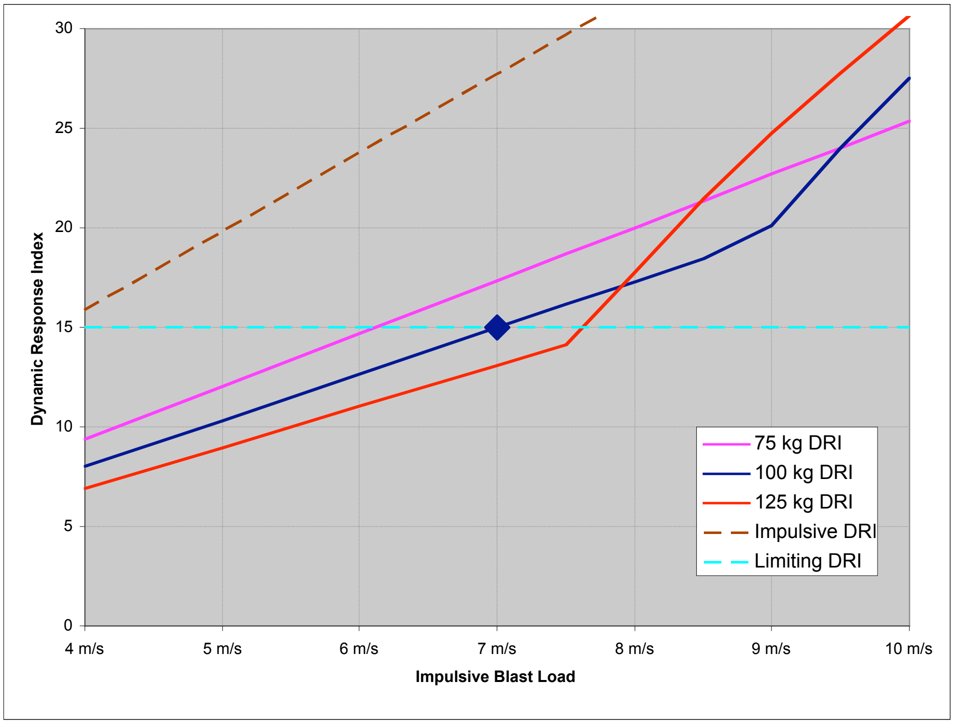

Figure 6. Variation in DRI with crew weight and initial blast impulse.

Interestingly, the lighter occupant never has a problem with bottoming out the seat, even up to 10 m/s of impulse. However, the DRI experienced by this crewman is higher than for the heavier occupants over most of the range shown, and exceeds the DRI=15 limit at 6.2 m/s of initial impulse. This is because the ratio (M/q) is too low for this occupant (the damping force is too high).

The heavier seat occupant actually has a softer ride over much of the range, and doesn't exceed the DRI=15 limit until 7.6 m/s of initial impulse. However, because he has already bottomed out the seat, the rate of increase in DRI is much steeper after this point, and by 8.5 m/s of impulse he has the highest spinal compression of all.

The moderate weight 100 kg crewman reaches the designed DRI value at the designed impulse using the designed stroke. At slightly higher values of impulse the seat bottoms out, but this doesn't become a big problem until about 9.0 m/s, at which point the slope of the curve increases greatly. By 9.5 m/s, this results in higher spinal compression than for the lightweight crewman.

An important implication of this analysis is that <u>one can achieve a given level of DRI performance without using all of the stroke needed for an ideal (non-stroke limited) solution</u>. For example, suppose that we did not have the 232 mm of stroke needed to provide a DRI of 15 for our 100 kg crewman at 7 m/s without bottoming out. How well could we perform if we only had 200 mm available? Counter-intuitively, we could

<u>reduce</u> the damping force somewhat from 3107 kg/s to 2660 kg/s. The figure below shows the resulting performance for the 100 kg occupant as well as ± 25 kg.

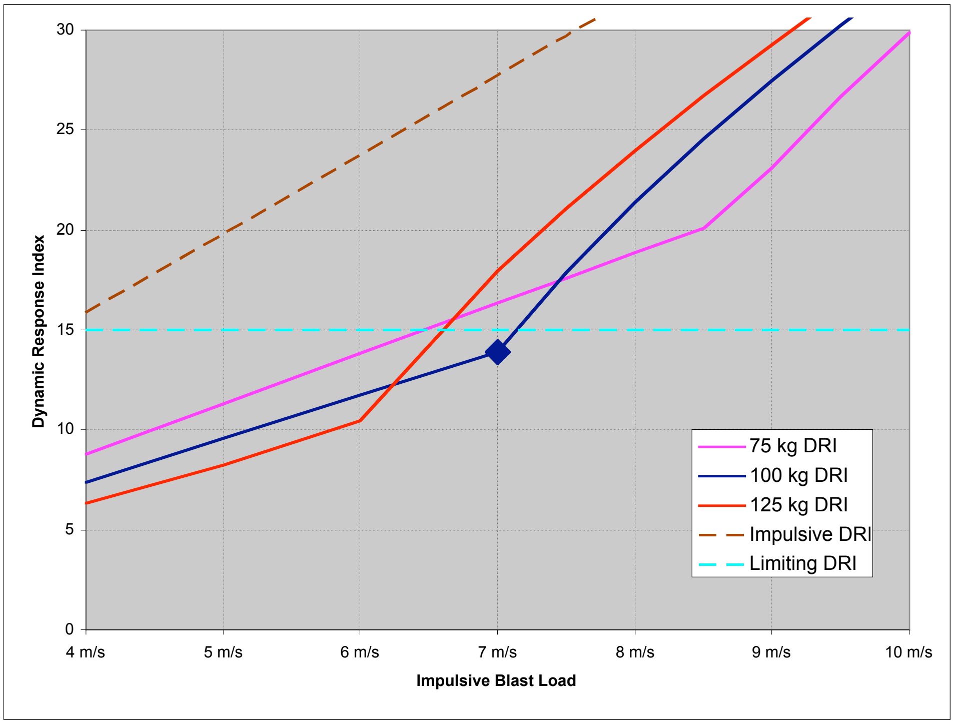

Figure 7. Variation in DRI for a non-ideal (stroke-limited) design.

The figure shows that we can actually achieve a lower DRI at the design load if we use a less stiff energy-absorber. This will result in the seat bottoming out against the floor, but the impact will not be hard enough to overcome the fact that the crewman had a softer ride on the way there. As a consequence, the overall spinal compression will actually be less. On the other hand, this design has virtually no margin - the DRI goes up steeply for any higher impulsive load. Also, the heavier crewman exceeds the DRI limit at a lower load (6.6 vs. 7.6 m/s) than in the ideal design. The lighter crewman actually has better survivability for lower blast loads, not exceeding the DRI limit until about 6.5 m/s (as opposed to 6.2 m/s for the previous design). This is due to the fact that lowering the stiffness (q) provides a softer ride for the lighter-weight crewman (better ratio of M/q). However, bottoming out now becomes a problem at about 8.5 m/s for this occupant, whereas previously it wasn't a problem even at 10 m/s.

A key question concerns the lowest possible spinal compression (or, equivalently, DRI) that can be achieved with a given amount of stroke, subject to a given impulsive load. The following figure shows this relationship, over the range from 5 to 8 m/sec of load, and 0 to 250 mm of stroke. Again, the term "minimum" refers to the minimum DRI achievable subject to the assumptions listed earlier. In practice, a lower DRI can be achieved due to cushioning in the body, springiness in the seat, and other factors. In the figure below, the minimum DRI is achieved with seats that bottom out.

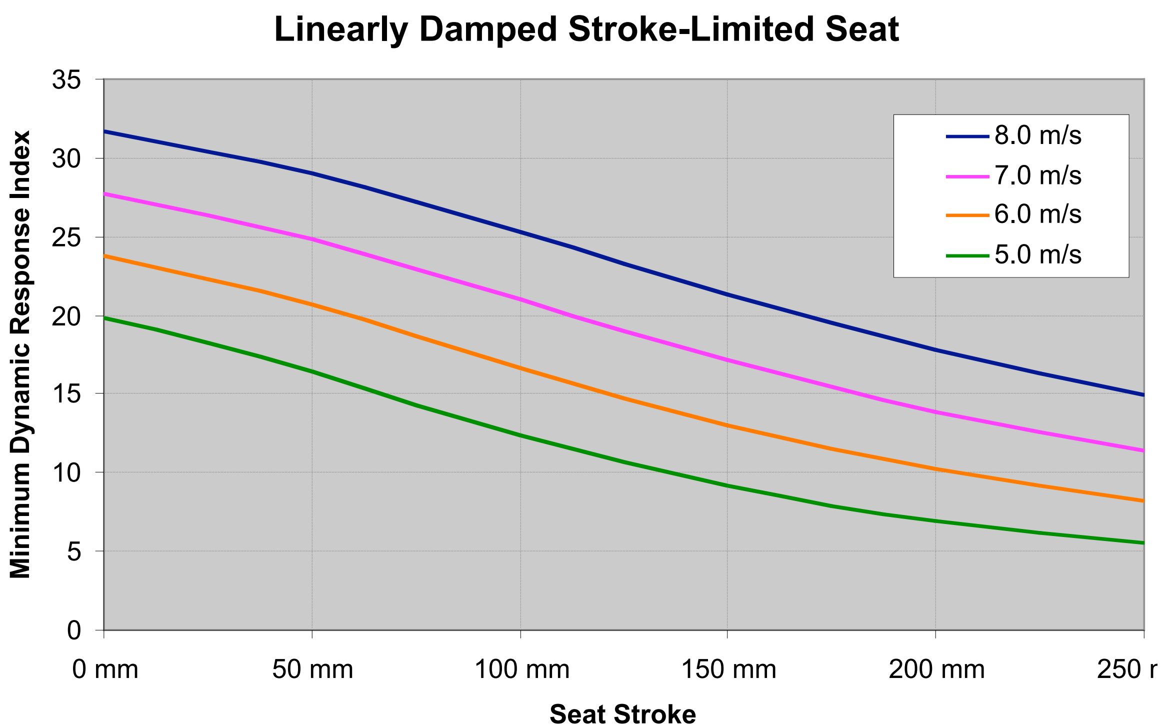

Figure 8. Minimum DRI vs. Seat Stroke vs. Impulsive Load

Impulsive Blast Loading V_o

The previous discussion has been concerned with mitigating the effects of an impulsive load of magnitude V_o, without regard to the question of how that load relates to the hull shape, vehicle standoff, blast load, and other real-world engagement factors. In fact, a wide variety of parameters affect the impulsive load delivered to the occupant of a seat subjected to a mine blast. These include the following:

- Size of the Mine (equivalent kilograms of TNT)
- Soil Conditions (Density, Moisture, Depth of Burial)
- Hull Size & Shape (V-Angle, Ground Clearance, Width)
- Sprung Mass of the Vehicle
- Blast Location Relative to Center of Gravity (CG)
- Initial Vehicle Motion (Jounce)

The figures below contrast two extreme cases, one producing very high impulsive loads, and the other very low. In general, high loads are associated with wide, flat-bottomed vehicles with low hull ground clearance. These vehicles catch a lot of the blast products (the soil thrown up by the explosion) and reflect them back to the ground. The loading gets worse if the mine is buried in a damp, high-density soil (for example, wet clay), since that tends to send more blast energy and momentum upwards. Also, if the blast occurs away from the CG in a lightweight vehicle, the blast will lift the vehicle higher and twist it over, resulting in an increase in effective V_o at the location above the blast.

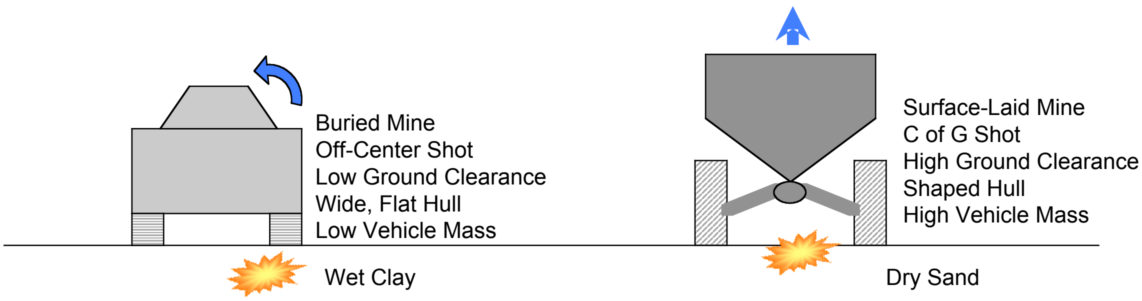

Figure 9. Contrasting blast loading conditions (high on the left, low on the right).

In contrast, low impulsive loads are associated with narrow vehicles with high ground clearance and, to some extent, shaped hulls. These features allow a large portion of the blast products to miss the vehicle entirely, and the shaping means that the reflected impulse goes laterally, instead of vertically, further reducing the load. A surface-buried mine in dry sand produces much less impulse than the same size mine buried in wet clay, because there is less material above the mine to throw at the vehicle, and because much of the blast energy is wasted in pushing the soft sand sideways and downward. Also, if the blast occurs directly over the CG, the vehicle will not experience any twisting motion, and the heavier the vehicle is, the more slowly it will be lifted off the ground, further reducing the impulsive load V_o.

Finally, one should take into account the fact that a combat vehicle rarely parks on a mine. For the most part, blasts occur while the vehicle is in motion, with all the automotive loads that entails. For example, it is entirely possible that the crewman could be bouncing downward in his seat at the moment of detonation, giving him an initial velocity in addition to that produced by the blast.

As a rough rule of thumb, the impulsive load produced on a given vehicle is proportional to the mass of explosive (M_E measured in kg), and inversely proportional to the vehicle sprung mass (M_V measured in metric tons). The constant of proportionality depends on the shape of the hull floor, the size of the hull, and the standoff to the ground in a manner that has been described in previous papers on the subject. Taking these factors into account, we can use the following simple equation to describe the blast load on the seat:

Impulsive Load V_o: $$V_o = k \cdot \left(\frac{M_E}{M_V}\right) \cdot R + V_{auto} \qquad (9a)$$

In this equation, k is the constant that takes into account the size and shape of the hull and soil parameters. R is the parameter that takes into account the potential for rotation of the vehicle for an off-center shot. Finally, V_{auto} is the constant that takes into account the initial automotive loads on the crewman in the seat. Reasonable values for R lie somewhere between 1.0 and 2.0, depending on the location of the blast and the moment of inertia of the vehicle (R=1 for a CG shot). Values for V_{auto} depend on the nature of the vehicle suspension, road condition, travel speed, and other factors. This parameter can assume both negative and positive values (the crewman could be moving up or down prior to the blast).

The parameter k is the most complex factor in the equation. This takes into the account the soil properties, size and shape of the hull, and standoff to the ground. Previous papers have dealt with this topic, and show that for a stiff prismatic hull with an angled floor the value of k varies with the half-width of the hull ($W_{1/2}$), the steepness of the V-angle (θ), and the clearance to the ground <u>at the edge of the hull</u> (C_{edge}) as follows:

Blast Loading Factor: $$k \propto \cos^2(\theta) \cdot \frac{W_{1/2}^2}{\left(W_{1/2}^2 + C_{edge}{}^2\right)} \qquad (9b)$$

With this information, we can rewrite our previous equation to show how the blast load varies with different design parameters.

Impulsive Load V_o: $$V_o = K_o \cdot \cos^2(\theta) \cdot \frac{W_{1/2}^2}{\left(W_{1/2}^2 + C_{edge}^2\right)} \cdot \left(\frac{M_E}{M_V}\right) \cdot R + V_{auto} \qquad (9c)$$

Here the parameter K_o describes soil effects and the energy content of the explosive.

In examining this equation, we can separate the parameters into two categories – those over which the vehicle designer has little or no control, and those over which he has great control. In the former category, we can include K_o, R, M_E, and V_{auto} (the designer can't control the location or size of the blast, or the initial automotive conditions at the time). In the latter category, we include θ (the steepness of the V-angle of the hull), $W_{1/2}$ (the half-width of the hull), C_{edge} (the clearance to the ground at the edge of the hull) and M_V (the mass of the vehicle). Again, this equation holds for a standard prismatic hull design with stiff sidewalls that reflect the impulse delivered by the blast products. It should be possible to reduce the impulse somewhat with a less reflective hull design, but this is not common among armored combat vehicles.

With this model it is possible to estimate the initial impulsive loading at the seat mount for a given vehicle. Furthermore, it is possible to estimate how that loading changes with the vehicle design, and with the size of the blast, location of the blast, and initial automotive conditions at the time. This loading estimate allows the calculation of the required seat stroke and damping needed to provide enhanced survivability for the crew during a blast event.

Summary

Combat vehicle designers have made great progress in improving crew survivability against large blast mines and improvised explosive devices. Current vehicles are very resistant to hull failure from large blasts, protecting the crew from overpressure and behind armor debris. However, the crew is still vulnerable to shock injuries arising from the blast and its after-effects. One of these injury modes is spinal compression resulting from the shock loading of the crew seat. This can be ameliorated by installing energy-absorbing seats which reduce the intensity of the spinal loading, while spreading it out over a longer time.

The key question associated with energy-absorbing seats has to do with the effect of various factors associated with the design on spinal compression and injury. These include the stiffness and stroking distance of the seat's energy absorption mechanism, the size of the blast, the vehicle shape and mass, and the weight of the seat occupant. All of these affect the spinal compression, as measured by the Dynamic Response Index. This paper presents a simple analytical model which ties together all of these variables, showing the effect of different energy-absorbing designs on crew survivability over a range of blast conditions. The analysis shows that the most important factor in determining the capability of the system to prevent injury is the stroking distance available to the energy-absorption mechanism. In addition, the analysis shows the limits of performance available to any seating system, and also how to optimize the seat design to produce minimum spinal compression for any given set of design parameters.