Analysis of Design Range for a Stroking Seat on a Stroking Floor to Mitigate Blast Loading Effects

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ABSTRACT

Army ground vehicles are continuously being enhanced to mitigate warfighter occupant injuries during severe vertical loading caused in an underbody blast event. Energy absorption from stroking seat is one of the commonly used design feature. In addition to this, another design feature that is increasingly being utilized is stroking floors. However, the effectiveness of a stroking seat when mounted on a stroking floor may depend on many parameters such as weights of seat/floor system, stiffness characteristics, payloads and the characteristics of the blast itself. This paper presents a comprehensive design analysis of such a stroking seat on stroking floor system and the optimal design points that can mitigate the occupant injury to a range of input parameters. One key conclusion from the study is that blast-mitigating seats must not be designed as isolated subsystems but with careful consideration of how they interact with other blast-mitigation design features as stroking floors.

Keywords*:* *Energy Absorption, IED, Blast, Stroking Seat, Stroking Floor, Occupant Injury, Design Optimization, blast mitigation*

1.0 INTRODUCTION

Army ground vehicle designs are continuously being enhanced to withstand high levels of underbody blasts in response to the ever-increasing threats seen in the battle field [1]. One of the major contributors of occupants injury in a underbody buried charge blasts is the very high accelerative load seen by the vehicle as a whole including the vehicle cab structure, interior components, seats and eventually the occupants [2]. In order to mitigate the blast effects, vehicles are designed with various underbody hull designs to deflect and dissipate the blast energy [5]. Further up the loading path, several other interior blast mitigation technologies are employed such as energy absorbing seats or vertical stroking floors [3].

Two major parameters in designing an effective energy absorbing (EA) feature are the loading condition (such as the peak accelerative force) and the size of the occupant [6-7]. For example, a stiffer EA feature is needed to mitigate higher loads and heavier occupants. In addition, due to the extreme range in the mobility and other operational requirements in the battlefield, there is also a need even for light tactical vehicles to carry higher payload including soldiers, their supplies, Personnel Protective Equipment (PPE), ammunitions, etc. As this payload can vary over a wide range throughout the operation, a successful blast mitigation design must take it into account while designing optimum floor and seat stroking mechanisms, even if they are designed to act relatively independent of each other [10-11]. This design becomes even more complex when a stroking seat is mounted on a stroking floor due to the closely coupled dynamics of these two sub-systems.

This paper presents a comprehensive design analysis of stroking seat on a stroking floor, which was performed in the CAMEL (Concept for Advanced Military Explosion-mitigating Land) program that was developed at TARDEC as part of the Occupant Centric Platform, Technology Enabled Capability Demonstrator (OCP-TECD) program.

2.0 MODEL SETUP

One interior design concept considered each occupant seat on an individual pod like setting as shown in Figure 1 wherein the occupant seat was mounted on a stroking or a suspended floor system and independent from the other pods.

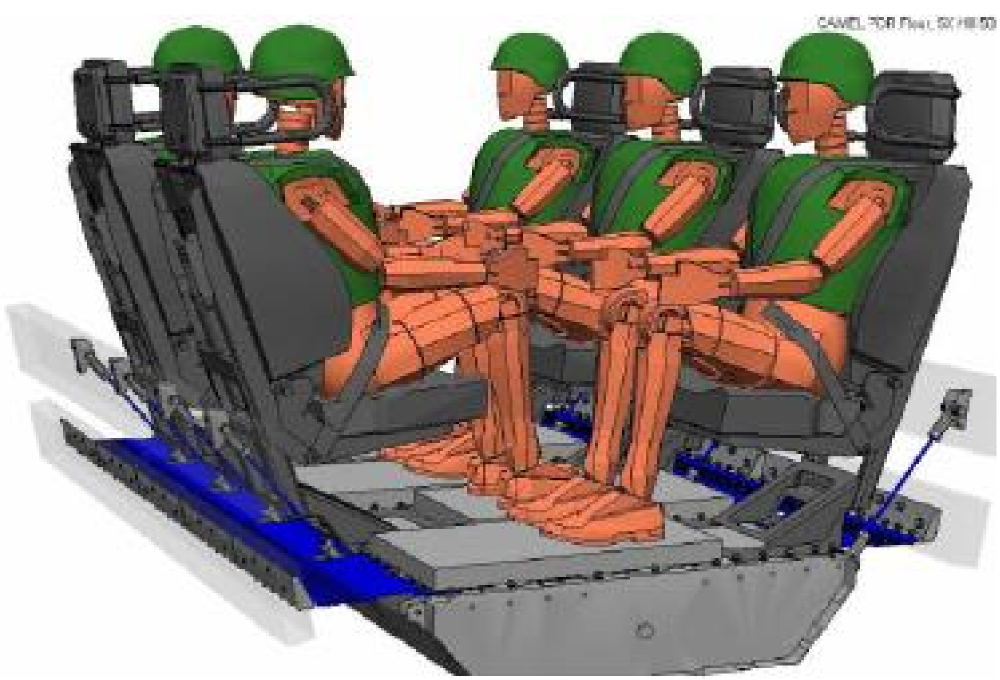


Figure 1: CAMEL Seating Concept

A fast running model was developed using the computational solver called MADYMO (Mathematical Dynamics Model) [8-9]. The model, as shown in Figure 2, consists of Vehicle hull with stroking floor with a specified EA characteristic. An energy absorbing seat is mounted on the floor. The occupant positioned in this picture is a Hybrid III 50th percentile Male ATD [13] with the masses of PPE and other gear are added to the mass of the ATD. The simulations were carried out by applying high acceleration to the hull and the floor and seat systems respond based on the inertial and stiffness characteristics. The occupant lower lumbar load was tracked as an injury response.

The baseline mass of the floor was 34Kg, representative of the vehicle floor pod, and the stroking parts of the seat was set at 50Kg. It was also assumed that the entire energy absorption feature was plastic deformation and no elastic energy would be stored for rebounding. Loading of the hull was enforced through vehicle acceleration for the reason that the hull mass would then not affect the simulation results, unlike force or impluse.

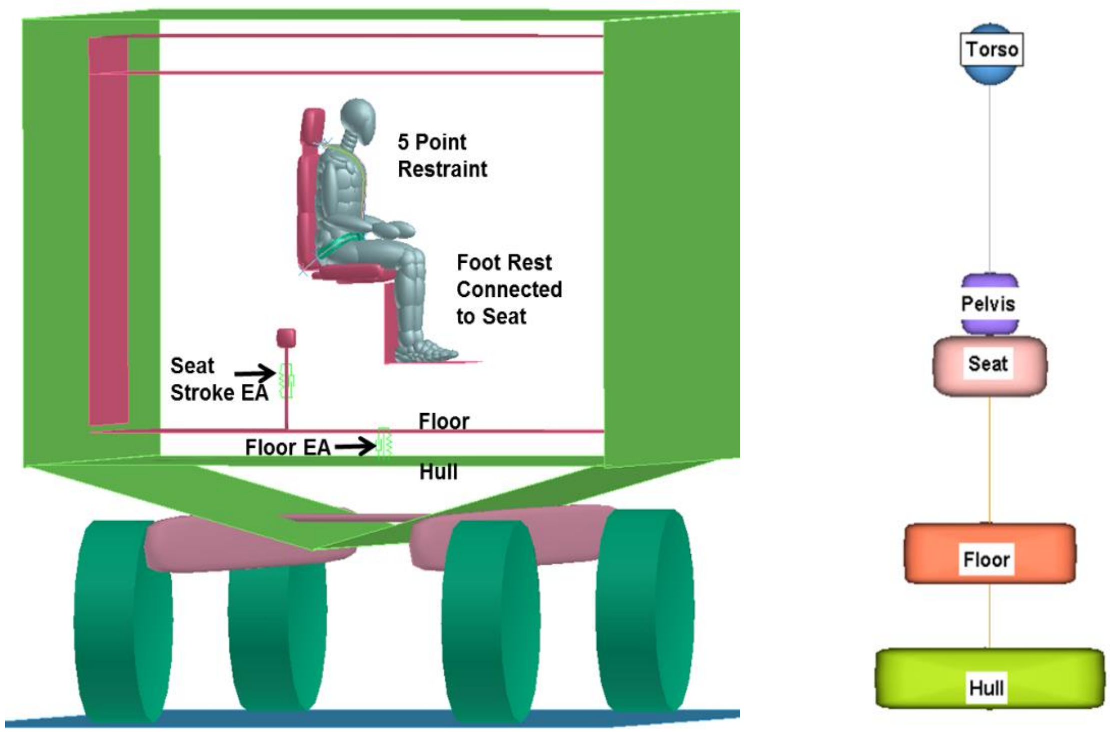
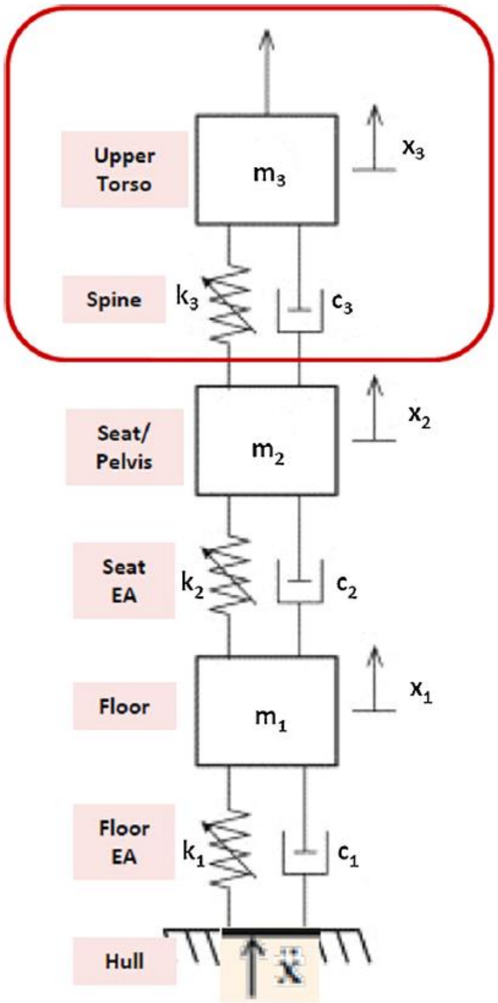


Figure 2: MADYMO Model of Stroking Seat on Stroking Floor

Additionally, a more simplified spring-damper-mass model was created in MADYMO that represents the dynamics and interactions of the seat-floor-dummy systems. This model is shown on the right side of Figure 2. This simplified model was also modeled as a simple 3-degree of freedom (DOF) system as shown in Figure 3. Results from a simple forward-marching integration scheme of this system of differential equations computed in an excel spreadsheet were used to validate trends from the two MADYMO models. In the simplified models, the Dynamic Response Index (DRI) [12] was used as the occupant injury metric, while in the full MADYMO model, the lumbar load load cell was tracked to denote occupant injury.



Assume: $z_3 = x_3 - x_2;$

$z_2 = x_2 - x_1;$

$z_1 = x_2 - x$

$$m_3\ddot{x}_3(t) = F_{spring3} + F_{damper3}$$

$$m_3\ddot{x}_3(t) = -k_3(x_3 - x_2) - c_3(\dot{x}_3 - \dot{x}_2)$$

$$m_3(\ddot{z}_3 + \ddot{x}_2) = -k_3 z_3 - c_3\dot{z}_3$$

$$\boldsymbol{m_3\ddot{z}_3(t) = -m_3\ddot{x}_2 - k_3 z_3 - c_3\dot{z}_3}$$

$$m_2\ddot{x}_2(t) = -F_{spring3} - F_{damper3} + F_{spring2} + F_{spring2}$$

$$m_2\ddot{x}_2(t) = k_3(x_3 - x_2) + c_3(\dot{x}_3 - \dot{x}_2) - k_2(x_2 - x_1) - c_2(\dot{x}_2 - \dot{x}_1)$$

$$m_2(\ddot{z}_2 + \ddot{x}_1) = k_3 z_3 + c_3\dot{z}_3 - k_2 z_2 - c_2\dot{z}_2$$

$$\boldsymbol{m_2\ddot{z}_2(t) = -m_2\ddot{x}_1 + k_3 z_3 + c_3\dot{z}_3 - k_2 z_2 - c_2\dot{z}_2}$$

$$m_1\ddot{x}_1(t) = -F_{spring2} - F_{damper2} + F_{spring1} + F_{spring1}$$

$$m_1\ddot{x}_1(t) = k_2(x_2 - x_1) + c_2(\dot{x}_2 - \dot{x}_1) - k_1(x_1 - x) - c_1(\dot{x}_1 - \dot{x})$$

$$m_1(\ddot{z}_1 + \ddot{x}) = k_2 z_2 + c_2\dot{z}_2 - k_1 z_1 - c_1\dot{z}_1$$

$$\boldsymbol{m_1\ddot{z}_1(t) = -m_1\ddot{x} + k_2 z_2 + c_2\dot{z}_2 - k_1 z_1 - c_1\dot{z}_1}$$

Figure 3: Three DOF spring-mass-damper system

2.1 Seat and Floor Stroking Characteristics

Figure 4 shows the energy absorption (EA) or stroking characteristics of the floor and seat systems. The seat system includes energy absorption due to both the deformation of the seat structures as well as the main EA mechanism of the seat. The maximum allowed stroke of the seat and floor EA systems is controlled in the model using the quick ramping up of the EA characterisitc curve at the end where the deformation bottoms out.

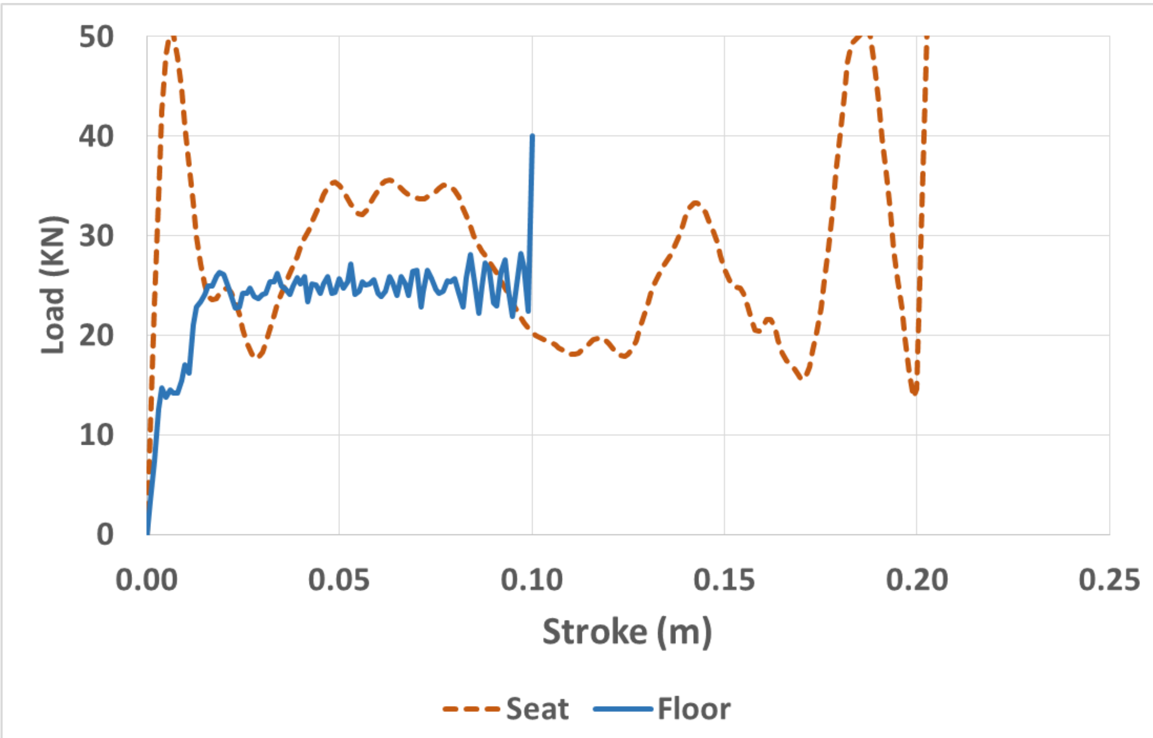


Figure 4: Seat and Floor EA Characteristics ("Baseline")

3.0 NUMERICAL ANALYSIS METHOD

For this study, a generic vertical blast triangular accelerative pulse [4] shown in Figure 5 was applied to the vehicle hull body in both the vehicle model with ATD and the simplified spring-mass systems. The duration of the pulse is 5 msec and peak is 350G. This corresponds to a peak velocity of the vehicle hull of 8.7 m/s at 5 msec.

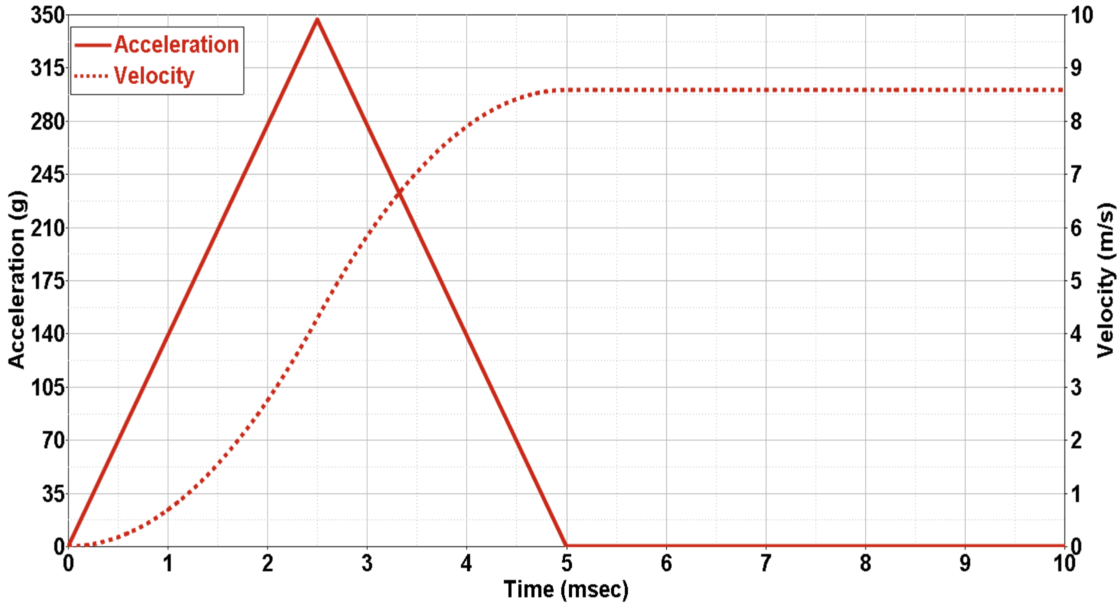


Figure 5: Vehicle Vertical Loading Pulse

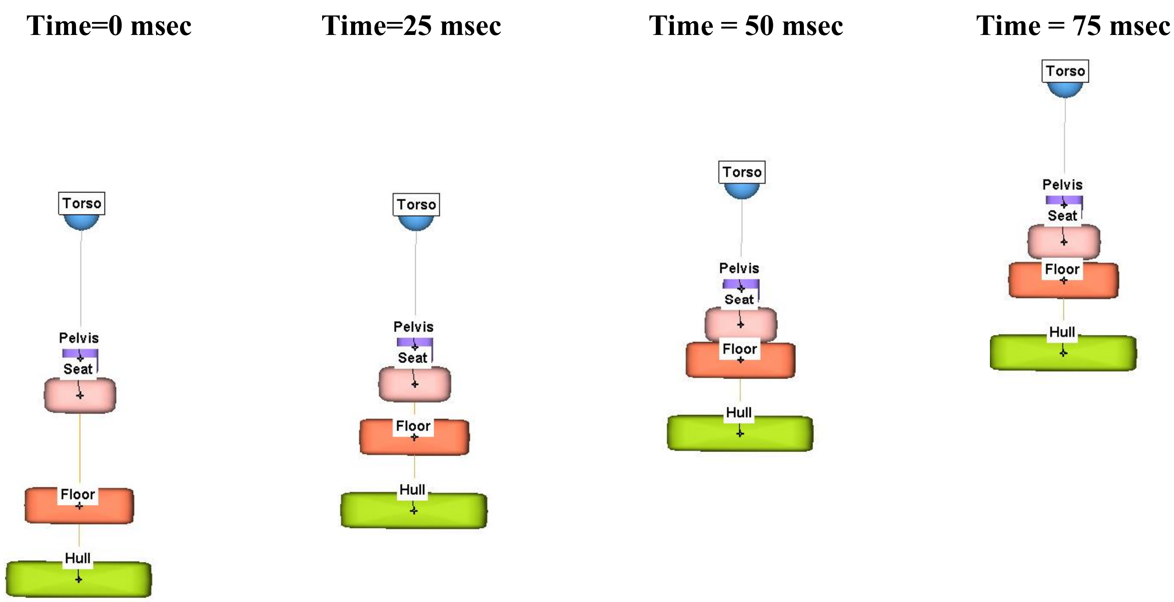


Figure 6: Simple Spring-Mass System – Deformation Sequence

Figures 6 and 7 show the animation sequences of the Simple Spring-Mass system and the Vehicle-ATD simulations, respectively, for the selected parameters of seat and floor characteristics shown in Figure 4. As can be seen from the simulation snapshots, both the seat and floor stroke as the vehicle is accelerated upwards, thereby absorbing energy and aiding in blast mitigation. Due to the inertia of the upper torso, lumbar spring in the spring-mass system was loaded in compression as seen at the 50 msec snap shot. Similar lumbar loading in compression is present in ATD simulations and confirmed in load cell results, however cannot be seen visually in the picture since the dummy's lumbar spine is not visible.

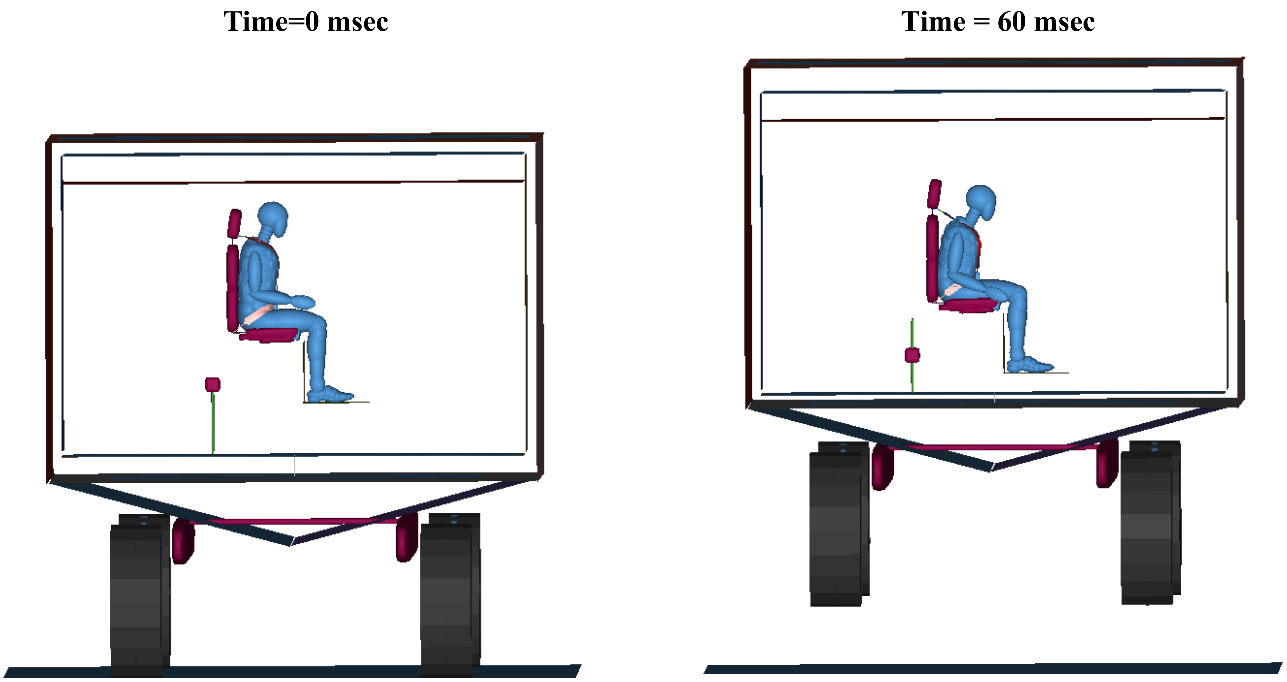


Figure 7: Cab-Floor-Seat System – Deformation Sequence

The time history acceleration and velocity responses of all the subsystems in the simulation are shown in Figure 8. The velocity response curves clearly illustrate the lags in peak responses that arise due to the dynamics of the simulation. The point at which the velocity of a certain part reaches the velocity level of hull indicates either the bottoming out (end of the allowable stroke) or exhaustion of inertial force from that body. In Figure 8, it may be seen that the floor seems to have completed its full stroke before the seat even starts stroking. The seat stroking continues well after the end of floor stroke and the upper torso velocity peaks after the seat stroke is exhausted.

Similar time-history responses were observed from the full Vehicle-ATD level simulations. In addition, lower lumbar loads from the ATD were also obtained from the simulations, and showed the same trends.

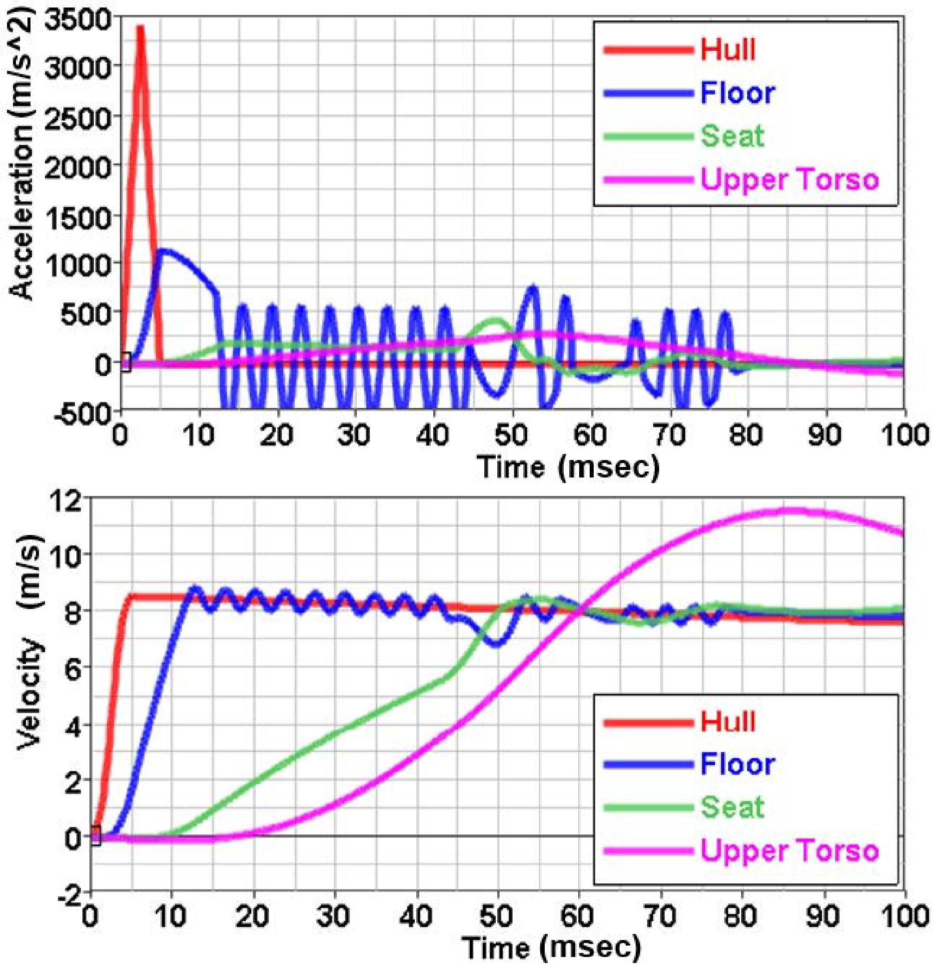


Figure 8: Responses from Simple Spring-Mass System

The iterative analysis to explore the design parameter space was carried out in the following steps:

(1) Determine the effectiveness of stroking floor at the baseline condition with a stroking seat.
(2) Determine the effectiveness of stroking floor at different seat and floor EA stroking characteristics. The seat EA curves were scaled from 0.4 to 1.3 and the floor was locked/non-stroking.
(3) Expand the floor spring scalings to 1,2,3,0.5 and locked condition. Vary the floor pod mass from 34kg to 64kg

Please note that "baseline" refers to the configuration where both seat and floor stroke with EA characteristics as shown in Figure 4. Also, the words "locked" and "non-stroking" are used interchangeably in this paper to denote lack of an EA feature.

4.0 ANALYSIS RESULTS

4.1 Baseline –Stroking floor vs Locked floor

The seat load vs. stroke response and lower lumbar load of the occupant from the full vehicle-ATD simulation are shown in Figure 9 for two scenarios.

(a) Locked or non-stroking (NS) floor, and stroking seat with EA

(b) Stroking floor and seat with EAs (also referred to as the baseline design)

In (a), as may be observed in Figure 9, the seat strokes completely through the entire allowed range (0.185 m) when the floor is locked. When the floor is allowed to stroke, it adversely affects the seat stroke preventing it from providing the full benefit of EA, and limiting the seat stroke to about 0.03 m. The effect of this difference in the dynamics is seen in the lumbar load of the ATD. When the seat stroke is reduced, the lumbar load peak value increases. When the seat strokes more as a result of locked floor, lumbar load is reduced. This result was counter-intuitive at least for the parameters under consideration, as a design with two stroking EA systems results in a higher occupant load than when just one strokes.

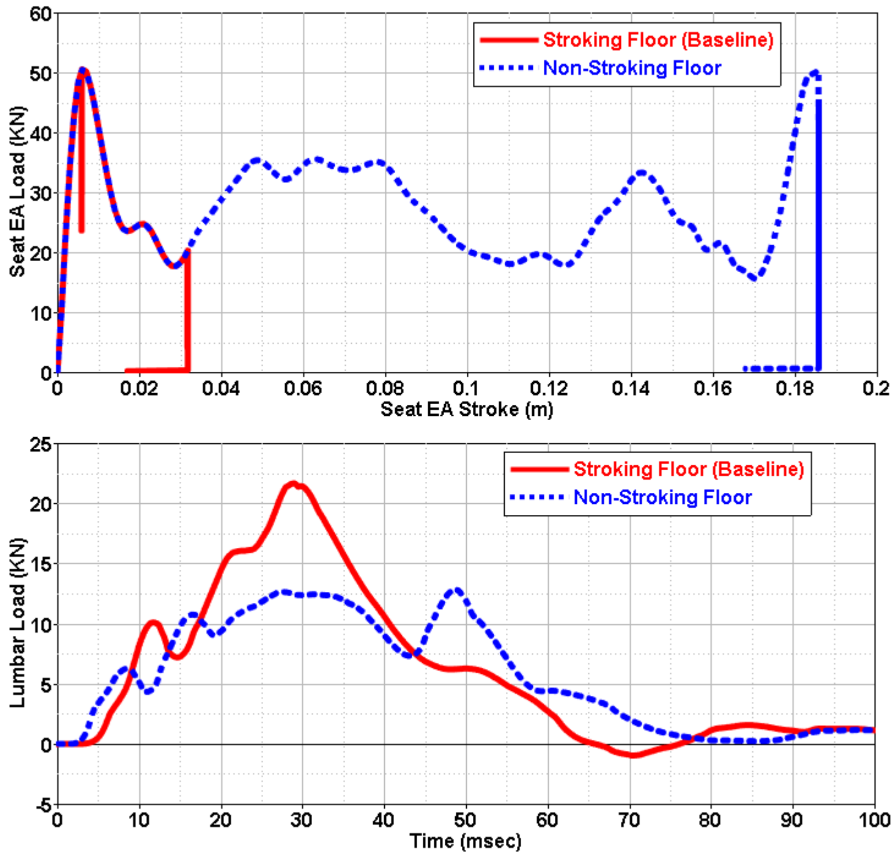


Figure 9: Seat and Occupant Response

4.2 Effectiveness of Stroking Floor

To further investigate the counter intuitive result observed in the baseline analysis (Sec 4.1), the study was expanded by varying the design variables with the goal of exploring the design space more completely. The baseline seat EA characteristic curve from Figure 4 was scaled from 0.4 to 1.3 of the baseline. The baseline floor EA from Figure 4 was used in one case and floor was completed locked (no stroking) in another case. The results from this study are shown in Figure 10. The original two baseline design points explored in the previous section are shown as blue (B) and green (G) circles. As may be seen from the figure, the two design points happens to be in a region of the design space where the stroking floor results in higher occupant lumbar load (red arrow L1). However, for a softer seat EA region (EA scaled below 0.9), a stroking floor would be beneficial. For example, it is possible to arrive at a design shown as an yellow circle (Y) in Figure 10 where the stroking floor and stroking seat with EAs of 100% and 80% of their respective baseline EAs (Figure 4) yield a lower occupant lumbar load (green arrow L2).

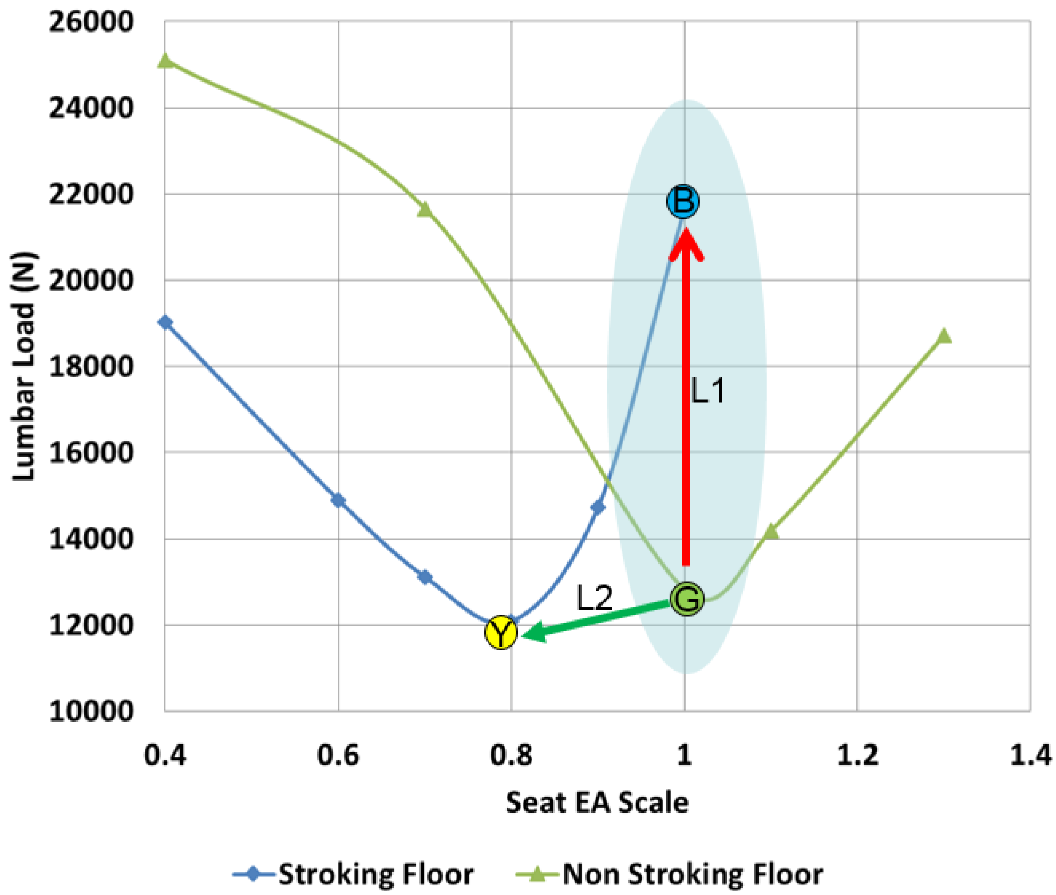


Figure 10: Effectiveness of Floor Stroke at 350G Vehicle Pulse

The study was further expanded to include the Floor EA properties as a variable. The floor EA curve was scaled from 0.5 to 3 in addition to the locked position. The results of this analysis is shown in Figure 11. A design combination of Floor EA scale factor of 0.5 combined with Seat EA scale factor of 0.8 results in the lowest lumbar load (purple X), over the entire range of parameters in this study. However, the floor EA of scale 1 results in a shallow curve which indicates a more robust design point wherein any changes in seat EA characteristics will not result in a large reduction in occupant injury performance. Again, all scale factors correspond to baseline EA values from Figure 4.

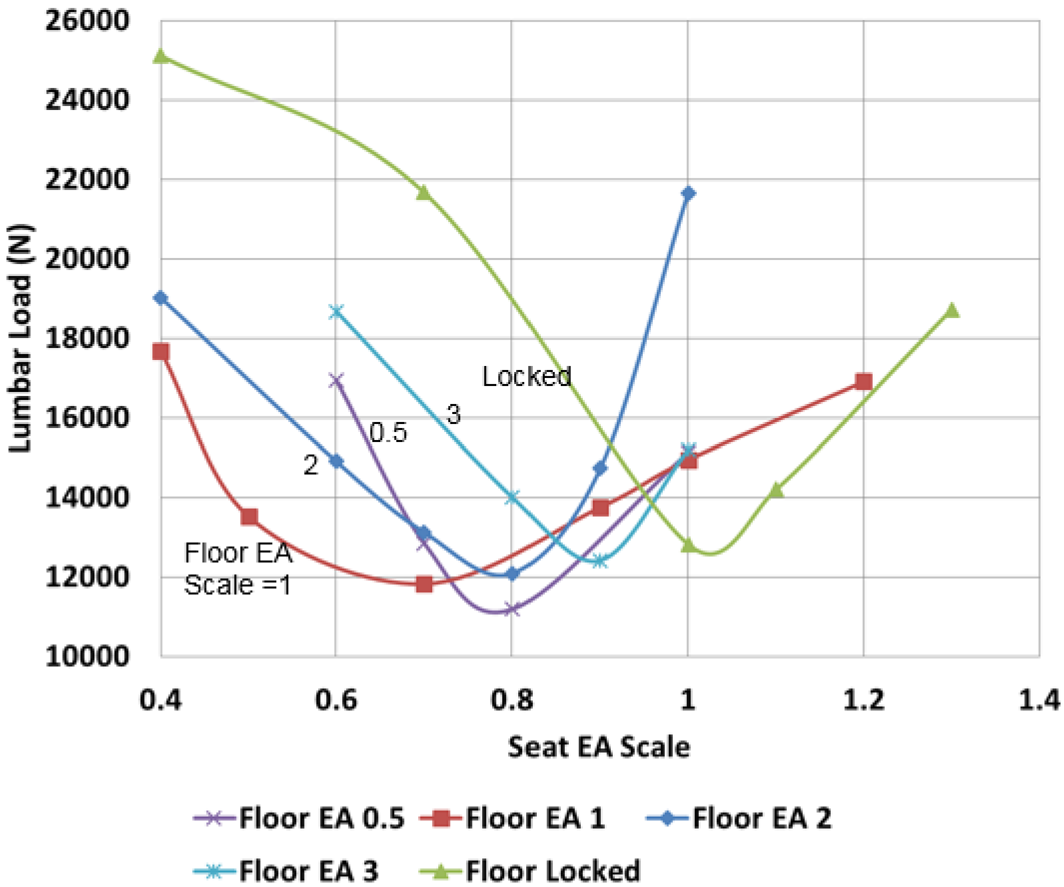


Figure 11: Effect of Floor Stroke EA

4.3 Effect of Variability in Floor Mass

As mentioned earlier, there are operational needs to vary vehicle payload, and hence the mass attributable to the floor. This can be due to changes in the supplies, soldier gear, arms and ammunitions. Hence it is imperative to consider that variation in the design of the stroking floor system as any change in floor mass could potentially move the design away from the optimal point to a significantly degraded performance. Figure 12 shows a simple study of this effect. The mass of the floor pod was changed from 32Kg to 64Kg and the lumbar load was observed for different seat characteristics. In both cases, the floor EA was as in Figure 4.

As it can be seen from Figure 12, an increase in floor mass may result in either an improved or degraded performance depending on the seat EA characteristics. Overall, in the system that was used for this study, an increase in floor mass results in a decrease in lumbar load. In order to minimize the effect of these variations of floor mass during operation, it is recommended to design a heavy floor system so that operational changes are minimal relatively speaking.

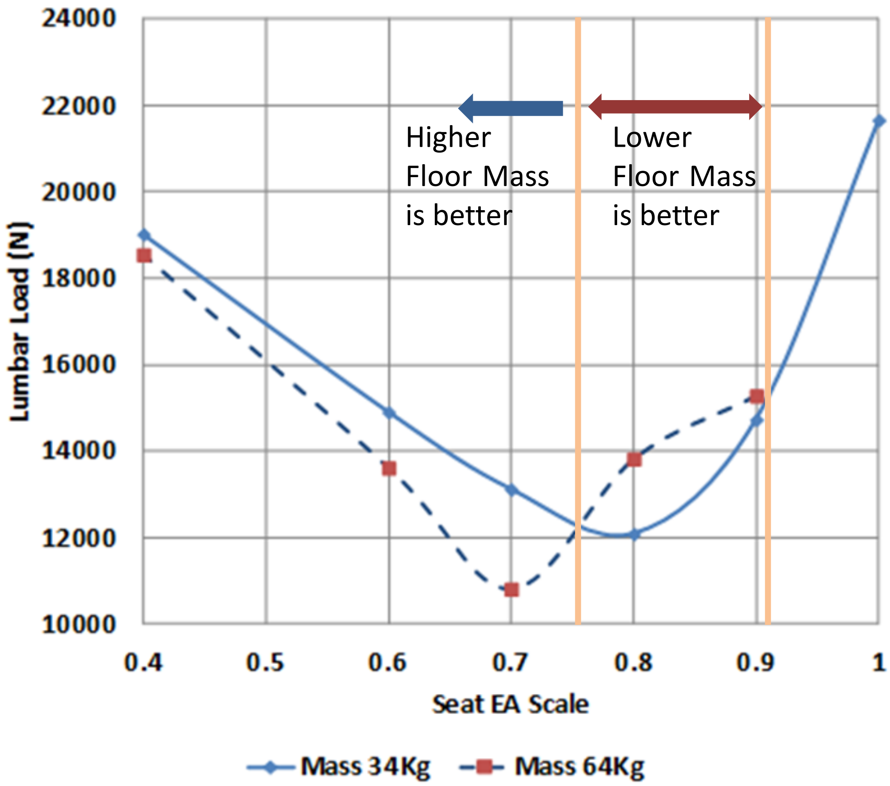


Figure 12: Effect of Floor Mass

4.4 Other Operational and Design Variabilities

In this analysis, a standard vehicle upward pulse of 350G peak was considered. However, the actual vehicle pulse can vary over a wide range depending on IED size, and theater conditions like soil type, depth of burial etc. The relative dynamic performance of the seat and floor systems depend on the vehicle pulse and hence any design solution needs to include the entire expected range of vehicle pulses. Figure 13 shows performance difference between stroking and non-stroking floors for a vehicle pulse of 175G. This figure is comparable to Figure 10 since the only difference is that the 350G pulse was used there. It can be seen from the plots in Figure 13 that as before, the stroking floor proves to be beneficial only for certain ranges of seat characteristics. Interestingly, at the baseline seat characteristics (seat EA scale of 1.0), the floor stroking did not result in any significant changes in the occupant injury performance. As compared to this, as may be seen in Figure 10 for the 350G pulse, the stroking floor was more effective until a Seat EA scale of 0.9, above which the fixed floor was more beneficial for lumbar injury. And at EA scale of 1.0, the fixed floor performed better than the stroking floor.

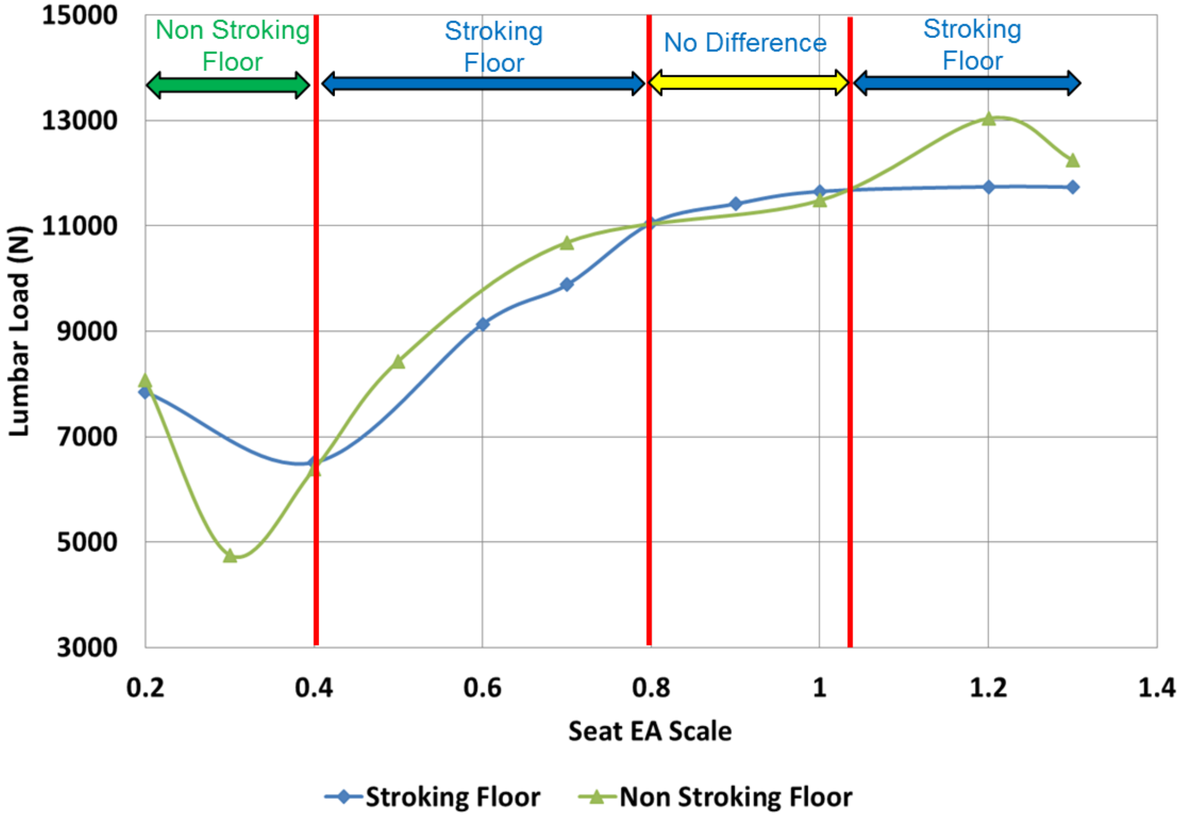


Figure 13: Effectiveness of Floor Stroke at 175G Vehicle Pulse

Similarly, there are other operational variations such as weight of PPE gear, ammunitions carried and the weight of the occupant. In this study, occupant is positioned with feet on the foot-rest attached to the seat system. However, a particular vehicle design may have the occupant feet directly on the floor. All these design and operational variabilities need to be included in the system-level evaluation for a complete and robust design solution, but have not been considered in the paper at this time.

5.0 CONCLUSIONS

- Three different models of different fidelity have been created to evaluate occupant lumbar loads in a vehicle cab environment consisting of a stroking seat mounted on a stroking floor mechanism.
- The introduction of a stroking floor in a vehicle system does not necessarily result in an improved occupant lumbar injury performance. In some cases, a locked or non-stroking floor may result in a better lumbar load performance than a stroking floor.
- The occupant lumbar load performance depends on the specific combination of seat and floor system masses and EA characteristics. Thus a need for system-level optimization of these design parameters is needed for the best occupant injury performance.
- An optimum design solution may not necessarily be a robust solution as it may be too sensitive to variations in the masses, especially floor masses. Hence it is imperative to consider the entire operating range of these parameters while arriving to a design solution.
- The optimal design solution is also dependent on the pulse characteristics as a design solution that works for a more severe pulse may not for a less severe vehicle pulse.
- Blast-mitigating seats must not be designed as isolated subsystems, as seat suppliers often do, but with careful consideration of how they interact with other blast-mitigation design features as stroking floors in the full-system environment.

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LIST OF SYMBOLS, ABBREVIATIONS, ACRONYMS

ATD	Anthropomorphic Test Device, or Dummy
CAMEL	Concept for Advanced Military Explosion-mitigating Land
DoA	Department of the Army
DoD/DOD	Department of Defense
Dof/DOF	Degree of Freedom
DRI	Dynamic Response Index
EA	Energy Absorbing, or Energy Absorption
FD	Force-Displacement
G	Acceleration due to gravity, 9.8 meter/sec2
Kg	kilogram
m	meter
MADYMO	Mathematical Dynamics Model by Tass International
M&S	Modelling and Simulation
Msec, ms	millisecond
NS	Non-Stroking
OCP-TECD	Occupant Centric Platform, Technology Enabled Capability Demonstrator
PPE	Personnel Protective Equipment
RDECOM	Research, Development and Engineering Command
TARDEC	Tank Automotive Research, Development and Engineering Center