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EVALUATION OF LIGHTWEIGHT MATERIAL FOR STRUCTURE, MINE BLAST PROTECTION, AND BUOYANCY FOR AMPHIBIOUS MILITARY VEHICLES.

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ABSTRACT

For this particular effort, TARDEC Center for Systems Integration (CSI) was tasked to lead an effort to develop an underbody kit that would serve multiple functions. The underbody kit would provide an additional 1,200 lbs of net buoyancy to enhance water mobility per the LAV. This program is in the development and testing phase with a prototype expected to be produced June of 2015. This program is one of multiple efforts to ensure the FOLAV meet all system requirements to keep the vehicle viable to 2035. In addition, the TARDEC concept/prototype must meet the same mine blast protection provided by the underbody D-Kit that was produced for the fleet of vehicles in 2010. This is a unique challenge as a combination of buoyancy, mine blast, and structural requirement on a ground military vehicle is novel idea. Vehicle weight and survivability requirements are difficult challenges on combat vehicles, to include the LAV, so the TARDEC solution would have to reduce the weight of the shell by approximately 60% and still achieve current survivability. Typically 20-30% reductions are considered aggressive, but 60% is usually unattainable.

INTRODUCTION: This paper only addresses the underbody buoyancy/survivability concept for PM-LAV. The new suspension package that will be integrated onto the LAV-25 offers variable ride height and significantly more ground clearance. This allows for a significant reduction in weight to achieve the same survivability capability. The current D-kit has some issues. One primary obvious issue is that it is heavy and the second is that the shape of the kit traps dirt, sand, mud, snow, and etc. between the kit and the underbody of the LAV. Secondly, the current underbody kit trapped the heat of the differentials. This is typical of any legacy vehicle that utilized an applique underbody kit. The simple challenge is to take a legacy vehicle that had to upgrade its protection that made it overweight and now add more upgrades that weigh even more and figure out a way to make it swim again and keep cost to a minimum.

To keep the R&D program cost to a minimum TARDEC leveraged upon it efforts from the Survivability Program that was funded by PM-LAV to develop a package of performance specifications, interface control documents and survivability concepts/innovations that would meet the survivability requirements in the LAV-CDD. One such critical innovation is the heel support that the soldier puts their heel on top of instead of resting the sole on the foot rest.

SURVIVABILITY INNOVATION: The Free Falling Heel Support Seat Base Side Mounted Foot and Leg Energy Absorbing Mechanism is a new concept breakthrough that has the potential to vastly improve the survivability of vehicles with regard to lower leg injury. Studies have determined that if the foot and leg can expand during a mine blast event, the survivability of the lower leg is vastly improved. Testing has shown that the compressive loading on the leg is up to 75% lower for this design over a typical foot rest, floor, or EA pad.

This is effective, however, the problem for using something like a peg in a combat vehicle is that the foot would not be comfortable and the foot would always be sliding off or the leg would be at 180 degrees only and this would not be something acceptable for the soldier and would require another platform for the foot to go on that would be susceptible to pulse. The foot pegs in Figure 1 shows what they would look like if incorporated into a seating design.

Figure 1: TARDEC EA Seat With Foot Pegs

The footpegs would allow for the feet to rest on the peg, but there is no support to keep the legs in an angle that is best appropriate to human factors. A very exhaustive study was conducted by engineers and scientists from BMW Group in Munich Germany (Innovationszentrum, Ergonomie and Komfort department) and Department of Biomechanics in Sports at the Technische University Munich, Germany. Their Journal "A Literature Review on Optimum and Preferred Joint Angles in Automotive Sitting Posture" [2] breaks down the optimum angle ranges for the various joints of the human body for the driver's station. In this study the mean value for recommendations are as follows:

Ankle angle: 98.26 °
Knee angle: 124° ± 7.8°
Hip Angle: 9.8°
Shoulder Angle: 28.26° ±10°
Elbow Angle 121.12° ±7.8°

Although there are many more seating positions in vehicles, the driver's is the most confining. So these values should hold similar results to other seating locations such as for scouts or troops.

Further investigations into the studies indicate that the overall mean value may not be the best angle and it may be an angle that is not optimal or comfortable. Research conducted by Kyung and Nussbaum indicated that there are two ranges for the optimum angle for many of the joints. Think of in the car, your leg is typically stretched out or is at about 90 degrees. Having it in-between is uncomfortable. The actual range for the knee in this study was 95 – 105 degrees (sedan) and 135 – 138 degrees (SUV) for the left knee.

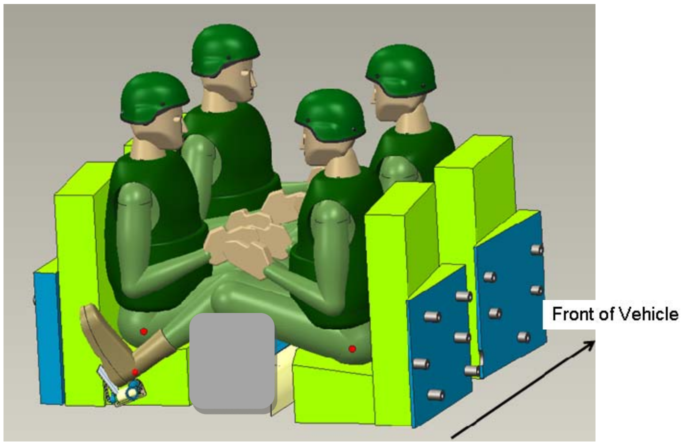


Figure 2: Isometric View of The Free Falling Heel Support Seat Base Side Mounted Foot and Leg Energy Absorbing Mechanism Installed in a Vehicle (initial concept).

Figure 2 shows how the seating would be for occupants in the rear of a military vehicle that is transporting troops or scouts. This design allows for the angle to be in the correct position and to be moved out of the way when the seat pan is moved up.

Unique to this design is the ability to allow the foot to slide out to prevent an excessive compressive loading to the leg but yet be properly supported so the soldier is comfortable. To allow for the soldier to be comfortable and yet prevent an excessive loading on the leg to break it, the back of the heel is supported by the larger blue cylinder. The corner where the back of the heel and the sole of the boot meet is supported by the yellow tubes. The endplate provides support for the sole of the foot.

The maximum compressive force that can be put one a single leg is 8 kilo-newtons [1] before injury results. Analysis on this concept has shown significant improvements over an energy absorbing pad or typical foot rests. Figure 3 shows the initial concept for integration.

LIGHTWEIGHT MATERIAL: For this particular effort, materials are being evaluated that can provide buoyancy within a structural shell that will be applied to the bottom of a military amphibious vehicle. As of 2015, we have found

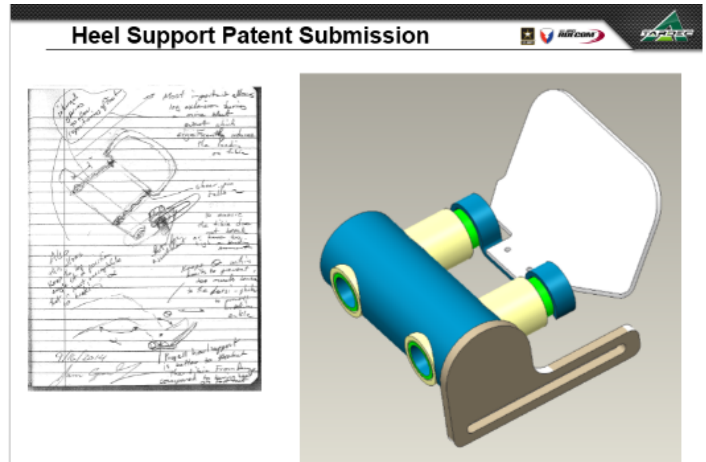


Figure 3: TARDEC Heel Support Innovation

that the NAVY and ARMY have both started to use Aluminum Honeycomb and foam filled panels. The Navy and Coast Guard are using them for Bulkheads, Flooring decks, False Decks and other areas that are interior to the ships. The Army has started to use the material for boxes, crates, building walls, floors, roofs, equipment structures, electronic instrument shelters, personnel shacks and more. The Army is also developing “Flexible Honeycomb and composite vehicle armor of hex and foam materials. Specifically, the materials that can be used for this application is as follows:

Honeycomb Material:

- Aluminum Honeycomb
- Plastic Honeycomb
- Stainless Steel Honeycomb
- Nomex with Phenolic coating

Non-metallic Foams

- Expanded Polyethylene Foam
- Expanded Polypropylene Foam
- Polyurethane Foam
- Vinyl Nitrile Foam
- Expanded Polystyrene Foam
- Styrofoam
- Syntactic Foam
- Nylon Foam

- Water & Tear Resistant EVA Foam

METALLIC FOAM: Material (FOAM) can be closed or open celled as needed for the application required. Closed cell is the best for an in water condition and can be machined and not have to worry about any water getting past the very first row of opened pockets. Using Aluminum Foam will give extra protection against mine blast and shrapnel when combined with Armor. Aluminum Foam cam be applied to your parts and in our case cavities to where a bottom and sides would be sealed and then just a S2 type composite of 2 layers would be light and seal the aluminum foam completely from water and moisture.

For this particular case, in order to meet the buoyancy requirement the average density needs to be less than 5 lbs per cubic foot. Based on this metal foams require a very large cell size and concern rises as to the potential for water entrapment. Sealing of the edges would be a requirement and any hole in any part of the sealed edge would be a potential for the entire aluminum foam product to trap water.

COMBINING SURVIVABILITY AND BUOYANCY: A conceptual design was innovated by TARDEC's Center for Systems Integration CSI. Specifically this design utilizes 5059/5083 for the structural shell. By meeting the survivability requirement with just the shell, the buoyancy material function was to provide buoyancy while swimming and would not compress under water, flammability requirements, temperature extremes of -40F and 160F. The weight of the material needed to be under 5 pounds per cubic foot to provide adequate buoyancy. This excluded metallic foams because they were too heavy and many syntactic foams. Since this kit would be used as a skid plate, it would sometimes deflect while driving over obstacles. This performance parameter required a material that would deflect and rebound to original shape. This criteria eliminated the use of honeycombs from being used in the design. Cost also drove the selection Expanded Polyethylene Foam with a density of 1.9 LBS per cubic foot. This material is used in the construction of marine fenders and bumpers that are used to keep naval ships from damage or docks. This material has the capacity to be compressed up to 65%. The foam is coated with a polyurethane liner to provide additional protection (Figure 4).

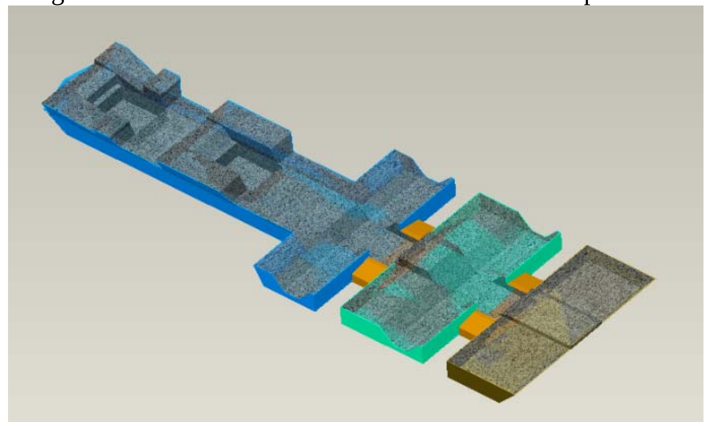
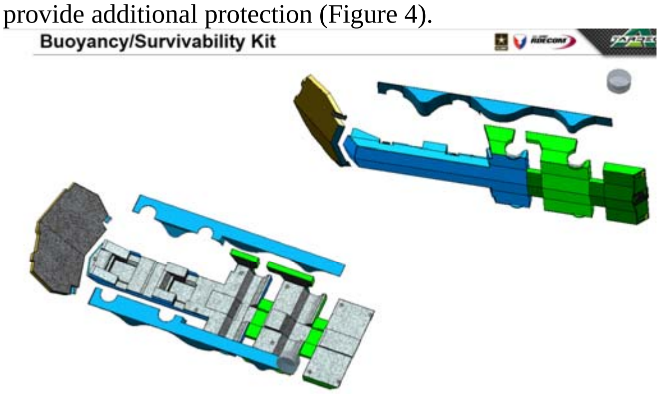


Figure 4: TARDEC Underbody Buoyancy/Survivability Kit



Configuration	Buoyancy Volume	Buoyancy Weight Reduction	Weight of Kit	Total Buoyancy Difference
½ 5059 Al Bottom, ¼ 5059 Trim Vane, 1/8 5059 Al elsewhere, 1.9 PSF foam	1.225 M^3	2700 lbs	928 lbs	1,772 lbs

Figure 5: Buoyancy Analysis of TARDEC Kit

The initial primary goal of the program was to provide the required buoyancy such that it off-set the weight gain from the mobility upgrade so the vehicle swimming capability would be brought back to LAV-A2 capability. To achieve this buoyancy requirement additional buoyancy kits were added to the design. Figure 5 shows all of the buoyancy kits that were added to achieve 1,700lbs of additional buoyancy.

TARDECs Thermal and Fluid Flow Analytics Team Analyzed the TARDEC underbody kit with the MOB upgrade weight to the baseline LAV-A2 and the LAV-A2 with the MOB Kit. Figure 6 shows that the freeboard and the metacentric height is 15% better than the baseline vehicle (LAV-A2).

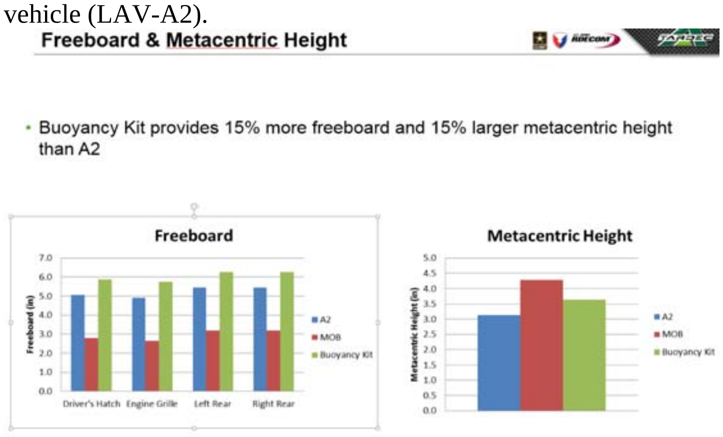


Figure 6: TARDEC Mine Blast/Buoyancy/Skid Plate Kit Concept Freeboard & Metacentric Height

One of the issues of adding buoyancy is the issue that if the center of gravity of the vehicle and metacentric height approach each other, the vehicle will become less stable. TARDECs Thermal and Fluid Flow Analytics Team performed the vehicle stability analysis on the TARDEC underbody kit solution and determined that the MOB upgrade with the TARDEC solution would be more stable in the water (Fig 7).

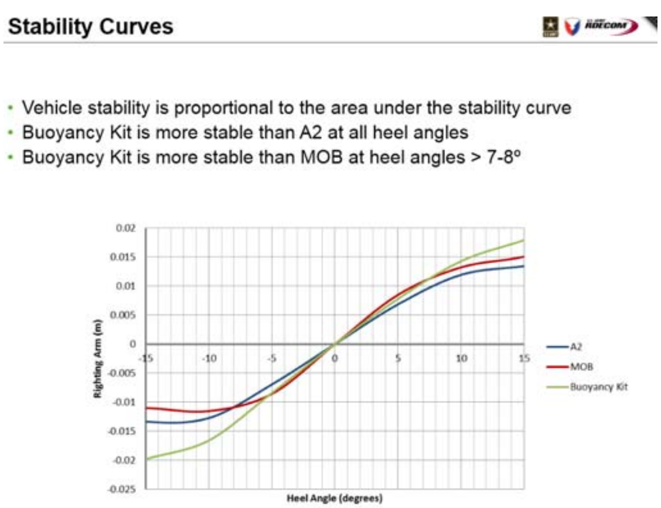


Figure 7: TARDEC Mine Blast/Buoyancy/Skid Plate Kit Concept Stability Curves

SURVIVABILITY: Funding and time did not permit a full survivability analysis in phase I of the program. However, TARDEC was able to leverage survivability efforts done in 2012-2013 on the LAV program. Based upon this work, the combination of the vehicle height and innovative foot rest would enable the LAV to achieve its threshold survivability and beyond and yet reduce the weight of the kit by 80%. The new kit would only weigh 20% of the original kit and provide significant buoyancy. Meeting threshold survivability and increasing the buoyancy of the vehicle by 1,700 lbs is a significant accomplishment. However, minimizing weight growth and maintaining buoyancy and achieving Objective survivability levels could be far more challenging. This would require determining where breech protection would be a focus and static deflection. This paper will focus on static deflection.

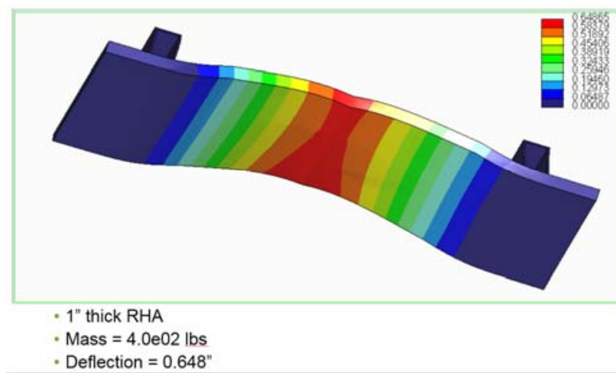


Figure 8: Steel Plate Analysis

Figure 8 shows the result of putting a given pressure load on a 1 inch thick steel plate with a shallow V that is off-set from a vehicle hull. The result was 0.648 inches of deflection. The effort is to determine how much lighter a design could be made to provide the same or less static deflection. Since we can get plate in 2-3 inch thicknesses, TARDEC analyzed a lower hull shape with sides and pocketing. Pro-E optimization was then used to determine the optimal size and shape of the pockets. By doing this the idea is to determine how much weight can be reduced. To parameters were that the plate must be ½ inch thick minimum and could be as thick as 2.375 inches. The material was switched from steel to aluminum.

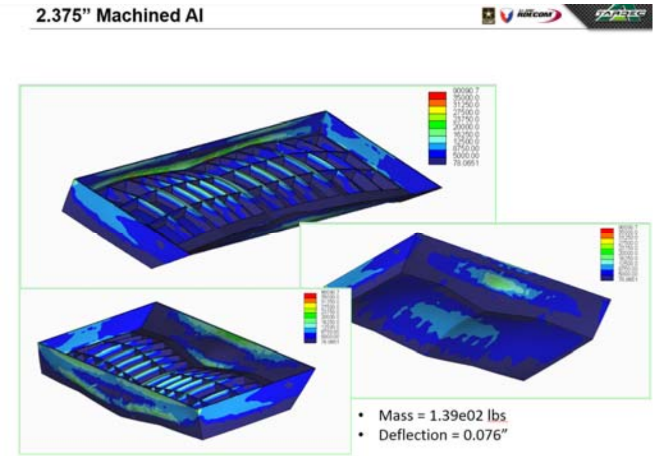


Figure 9: Optimized Analysis

By doing this the weight was one third of the original plate and the deflection was substantially reduced. This is actually an anticipated result as to how the structure could be stiffened. Analytically, the best result will be thin tall ribs if the parameters would allow for this condition. This result can lead to a false sense of security as the mine blast event is not static, but dynamic. Furthermore, if the loading is not uni-directional or any out of phase loading would have a significantly different result. In a mine blast event, a significant amount of energy is put into a vehicle structure and this causes a pulse to travel through the vehicle. Fig 10 shows a plate that is struck with a frag simulated projectile. Although much easier to see the pulse traveling through the plate in the video. A still image shows the deflection of the plate from the FSP between the two black lines.

Figure 10: Plate Deflection

The current design utilized an eggcrate shape that were not tall in comparison to the thickness of the rib. The rib height was limited to 2.375 inches in height. To evaluate the design for a pulse condition, the ribs were modeled in a pulse type condition. A sine wave at the top of the rib was blended to a straight line at the bottom of the rib. The design intent would be to start with a thick plate and mill out the pockets. Using the same material and rib height and thickness for the static design (figure 11) and pulse design, a deflection analysis was performed on the two conditions.

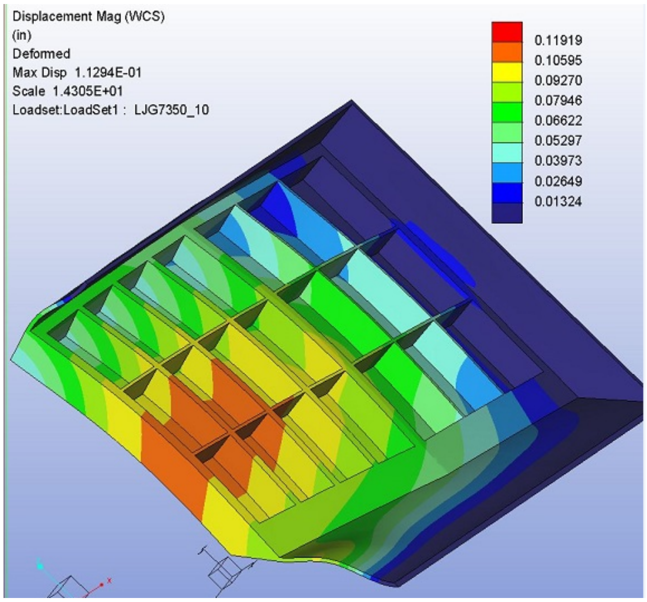


Figure 11: Static Deflection of Egg-Crate Structure from a Pressure Bubble.

Figure 11 shows that about 0.10 inches of deflection would result from a given pressure bubble loading. Figure 12 shows the maximum displacement to be approximately 0.13 inches of deflection for the same given pressure bubble loading. Even though the ribs are short and relatively thick for their given height, the dispacement of the structure is 30 percent greater for the structure that had a simulated pulse. Please note that the main stiffening center rib was not shaped to simulate a pulse and this would have further increased the deflection. However, if we consider the initial design of steel and a much heaver/thicker plate in figure 8, the egg-crate design allowing for the pulse has one fith the deflection as the original design and the weight is about one fith that of the steel plate as well. This is a substantial improvement over the original design and will significantly improve the performance of the kit. A futher benefit will result from high strain rate bucking. Honeycomb testing has shown that a 30% increase in the dynamic crush strength over the static crush stength for thicker honeycomb cores results when speeds of 500 ft/sec are tested in impact chambers.

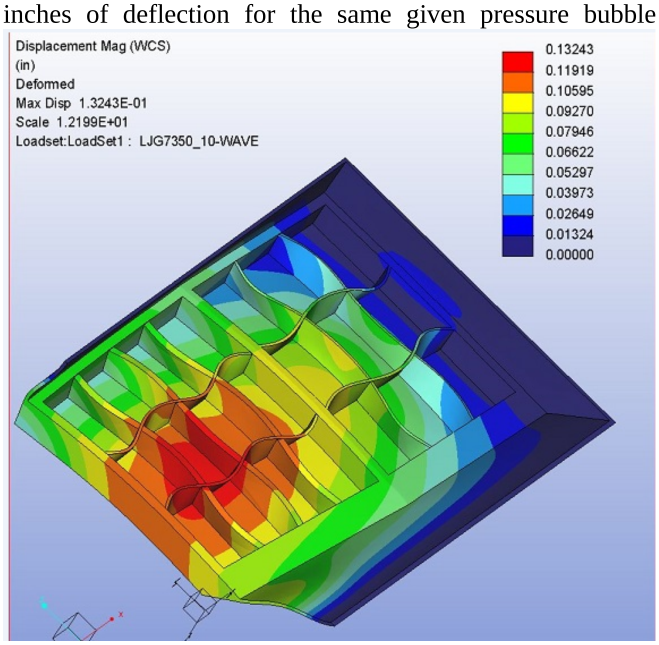


Figure 12: Static Deflection of Egg-Crate Structure with a simulated pulse structure.

Also, by combining the foam in an egg-crate structure, it will allow for better distribution of loading as stiffer/heaver foam can be put in areas that need reduction in deflection and the routing of the load path through the structure to parent vehicle. Typically the load is desired to be transferred to the side walls of the parent vehicle. This combination will enable better energy transfer and as a result increased survivability. Because the foam prevents dirt and liquids from filling the underbody hulls it prevents the possiblity of this foreign material filling the space between the underbody kit and the vehicle. This would result in the direct transfer of energy from the underbody kit and the vehicle.

NASCAR and NASA have spent considerable effort in dealing with occupant safety in high impact situations. Figure 13 shows a crash in automotive racing. The damage from this crash shows how NASCAR is utilizing energy absorbing foam to help mitigate energy being transferred to the occupant.

Figure 13: NASCAR Crash

One interesting note. In reading an article from Politico, General Chiarelli was briefed on how the military soldiers were seriously injured and would not be able to return to duty. “A subordinate showed him a bar graph depicting the number of soldiers determined by the Department of Veterans Affairs to be at least 30 percent disabled. The tallest column was on the far left. Those were amputations, Chiarelli thought or burns. Then he examined the graph more carefully. Burns were off to the right, accounting for just 2 percent of disable soldiers. Amputations were in the middle, at 10 percent. The big column, which represented 36% of the seriously injured soldiers, was labeled PTSD or TBI”. If traumatic brain injury which could be resulting from mine blast effects are that significant. This may lead to greater efforts to more accurately predict traumatic brain injuries from mine blast events.

CONCLUSION:

By combining energy absorbing foam and enhanced structural shapes, lighter and more survivable solutions can be developed for military vehicles. The initial efforts have shown that it is plausible to reduce the weight of an underbody kit that would use a solid plate by one fifth and yet reduce the dynamic deflection by another fifth. Because of the low cost of the energy absorbing foam (packaging material). That cost can offset the increased manufacturing cost for structural stiffeners. Further benefits are achieved by the foam preventing foreign material from getting in between the underbody kit and the vehicle. This factor is not considered in the testing of the vehicle, but is a real issue as one would expect by putting a V-shape under a vehicle that must travel through mud, snow, and sand. This initial research effort has shown substantial gains are possible and much more can be achieved as additional engineering, technology, and research is applied to smart energy management solutions for occupant protection for amphibious military vehicles.

REFERENCES

[1] Crash Analysis Criteria Description. October 2006 ed. Bergisch Gladbach: National Insturments, Workgroup Data Proessing Vehicle Safety, 2006. 142. Print.

[2] Ryan Capouellez, Review of Head Injury Criteria.

[3] Kyung, G., Nussbaum, M.A., 2009. Specifying comfortable driving postures for ergonomic design and evaluation of the driver workspace using digital human models. Ergonomics 52 (8), 939 953.

[4] General Chiarelli's Brain Crusade. (n.d.). Retrieved June 14, 2015, from http://www.politico.com/magazine/story/2014/12/general-chiarellis-brain-crusade-113827.html

[5] Finite Element Analysis with IMPAXX (trademark) Energy Absorbing Foams in Headliner Applications. (2015, June 30). Retrieved June 30, 2015, from http://msdssearch.dow.com/PublishedLiteratureDOWCOM/dh_030b/0901b8038030b1d4.pdf?filepath=automotive/pdfs/noreg/299-51549.pdf&fromPage=GetDoc

[6] Peacock, A. J. (2000). *Handbook of polyethylene: Structures, properties, and applications*. New York: Marcel Dekker.

[7] Eaves, D. (2001). *Polymer foams*. Shawbury, United Kingdom: Rapra Technology LTD.

[8] Bitzer, T. (1997). *Honeycomb technology: Materials, design, manufacturing, applications and testing*. London, United Kingdom: Chapman & Hall.

[9] Ashby, M. F., Evans, A. G., Fleck, N. A., Gibson, L. J., Hutchinson, H. W., & Wadley, H. G. (2000). *Metal foams: A design guide*. Boston: Butterworth-Heinemann.

[10] Lawrence, C., Fasanella, E. L., Tabiei, A., Brinkley, J. W., & Shemwell, D. M. (2008). *the use of a vehicle acceleration exposure limit model and a finite element crash test dummy model to evaluate the risk of injuries during orion crew module landings* (NASA/TM-2008-215198). Retrieved from NASA website: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080018587.pdf