DESIGNING A MORE SURVIVABLE SEAT SYSTEM: THE TEST AND EVALUATION OF A CRASHWORTHY OCCUPANT PROTECTION SYSTEM (COPS) FOR THE HMMWV

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ABSTRACT

U.S. Army trucks may be operated in severe operational environments under extremely stressful conditions which result in increased frequency and severity of crashes compared to similar trucks in the civilian fleet. Extensive research and development is ongoing to reduce the frequency of these crashes through crash avoidance technology but a significant number of crashes and subsequent injuries will continue to occur. Therefore, the U.S. Army TARDEC's National Automotive Center and Survivability Technology Area, in conjunction with the U.S. Army Safety Center, Ft. Rucker AL, and ARCCA, Inc. of Penns Park, PA, are taking on the challenge to develop safer, more survivable ground vehicle systems for our men and women of the armed forces. This paper summarizes research and analysis conducted on one of the Army's Light Tactical Vehicles, the High Mobility Multi-purpose Wheeled Vehicle (HMMWV). Utilizing the crash and injury database at the U.S. Army Safety Center, the object was to identify the types and frequency of HMMWV crashes and the mechanisms of injuries sustained by the occupants involved in these crashes. Countermeasures were identified, investigated and analyzed through research and assessed using computer crash simulation, drop testing, and inversion testing. Candidate countermeasures found to be effective will be integrated into a Crashworthy Occupant Protection System (COPS) mockup to demonstrate their compatibly with the vehicle platform. This concept is currently being refined to be compatible with multiple Army ground vehicles creating a Common Crashworthy Occupant Protection System (CCOPS). All or many elements of CCOPS will incorporate state-of-the-art crash and injury reduction technology, some of which could be retrofitted into current trucks or incorporated into new vehicle platforms such as the 21st Century Truck or Commercially Based Tactical Truck (COMBATT) vehicles.

OBJECTIVE

The objective of this analysis is to identify and determine the feasibility of innovative occupant crash protection systems that reduce the frequency and severity of crash induced injuries to front seat Army personnel. Our goal was to evaluate HMMWV crashworthiness and how it affects soldier survivability. We identified mechanisms of injury, generated performance requirements for new crash protection systems, performed tests to demonstrate the differences between various seats, and identified test methods for evaluating alternative designs. The primary focus of this effort was on frontal, frontal oblique, side, and rear impact mishaps. While vertical force mishaps were the subject of another analysis, our systems design considered this, as well as the rollover crash. The rollover crash is a highly dangerous crash and often includes some or all of the components of other crash modes. While we used the HMMWV as the object of our analysis, the methodology and results apply in general to all Army tactical wheeled vehicles. We established that many injuries in Army ground vehicles result from identifiable hazards.

Once we identified the hazards, we evaluated ways to eliminate or mitigate them through a systems approach. While we used the HMMWV as the object of our analysis, our goal was to identify countermeasures that the Army could apply to its entire ground vehicle fleet. This analysis has five Technical Objectives, each summarized below:

Technical Objectives/Methodology.

Technical Objective I: *Identify Hazards and Mechanisms of Injury.* The Army Safety Center (ASC) and other Army agencies maintain information from which crashworthiness engineers can derive hazards. We designed and conducted a data search that focused on selected mishaps involving frontal, frontal oblique, side, rear, slam downs and roll over crashes. ARCCA received the HMMWV mishap file electronically for approximately 2,900 HMMWV mishaps (included crashes and other reportable accidents). ARCCA engineers inspected the vehicle and recorded hazards. Users were also interviewed.

Technical Objective II: *Identify Mission and User Requirements.* The HMMWV mission and user requirements were examined to ensure that the crash protection requirements we developed were mission compatible and met user needs for vehicle operation. Our methodology was to research operational requirements documents (ORDs) for the HMMWV, HMMWV II, COMBATT and other information provided by NAC and located through our own research. We also interviewed and surveyed soldiers at Ft. Bragg and two National Guard units.

Technical Objective III: *Analyze Mishap Data and Determine Injury Costs.* ARCCA analyzed the data collected in Technical Objective I and visited ASC to do an in-depth review of selected mishap investigation reports to determine the associated injuries, fatalities and the mechanisms that cause them. Additionally, ARCCA performed an evaluation of the hazards within the occupant compartment of the vehicle utilizing the barrier crash test as well as a costs of injuries and fatalities analysis using DOD and DOT cost parameters.

Technical Objective IV: *Select & Evaluate Candidate Solutions.* Requirements were established to eliminate or mitigate the identified hazards and reduce their risk. We then searched for candidate systems to meet those requirements. Unable to find suitable candidates, system mockups were designed and developed to meet these solutions. The evaluation included inversion testing, drop tower testing and computer simulations, human factors evaluations and fit checks.

Technical Objective V: *Conduct Computer Simulations.* ARCCA conducted DYNAMAN simulations to compare the performance of the newly designed system to the current HMMWV seating and restraint systems. Simulations included frontal, frontal oblique, side, rear, and roll over using 5^{th} percentile female and 50^{th} and 95^{th} percentile males, as well as various seat/belt combinations.

Seat System Results

Because an off-the-shelf system that met the requirements could not be located in industry, ARCCA designed and fabricated an integrated occupant crash protection system mockup agreed to by NAC and ARCCA, that did meet the requirements. The Army and ARCCA also agreed that since we were "starting from scratch" we would expand our requirements definition based upon the mishap and hazard analyses. We agreed that the system should incorporate the following:

- Integrated lap/shoulder 3-point restraint system and integrated supplemental belt with a switch to prevent occupants from wearing the supplemental belt without the primary lap/shoulder belt
- High seat back strength
- Overall dimensions that will fit in the HMMWV occupant space
- Head restraint height to safely accommodate the 95^{th} percentile male
- Side bolsters to supplement lateral restraint that do not impede wearing required equipment (e.g., canteens)
- Pretensioners to remove slack in the restraint system at the time of impact, ensure timely retractor lockup, and initiate early crash ride-down
- Contoured seat bottom to assist with lower torso and buttocks restraint
- Seat bottom that incorporates a structural seat ramp to limit submarining of the occupant's lower torso under the lap belt
- Seat bottom designed to minimize dynamic amplification of loads and accelerations
- Fore/aft adjustable
- Minimization of shiny/reflective surfaces
- Compatibility with all four occupant positions
- Supplemental roll over protection to the occupant
- Safe and comfortable accommodation for the entire range of 5^{th} percentile female to 95^{th} percentile male with various standard gear configurations
- Weather resistant covering

Mockup Construction and Evaluation

ARCCA first constructed a mockup that we tested identically to the A1/A2 seat. We also conducted a comprehensive series of computer simulations as described in Technical Objective IV. Figures 11 and 12 on the next page show the mockup system.

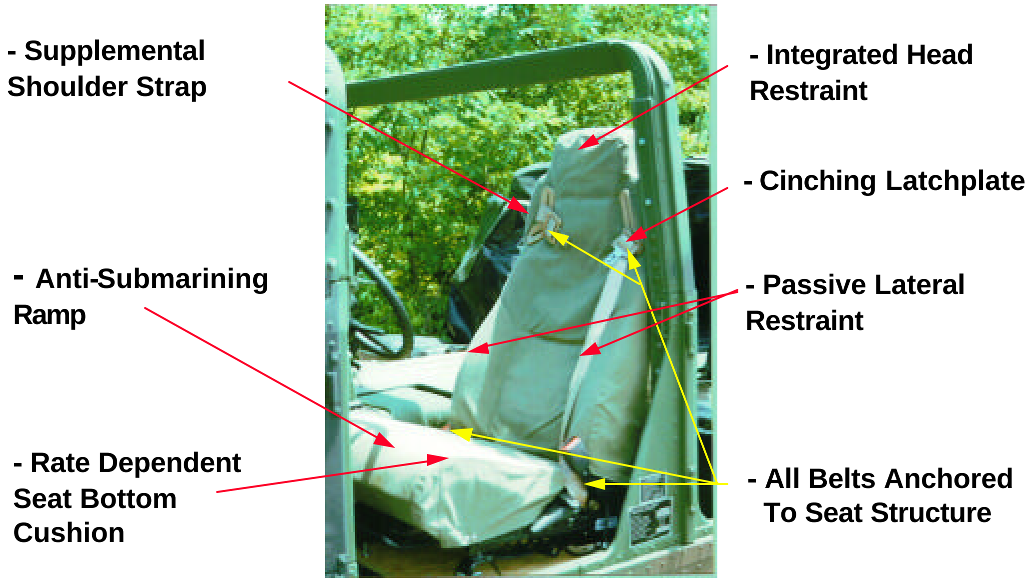

Figure 11

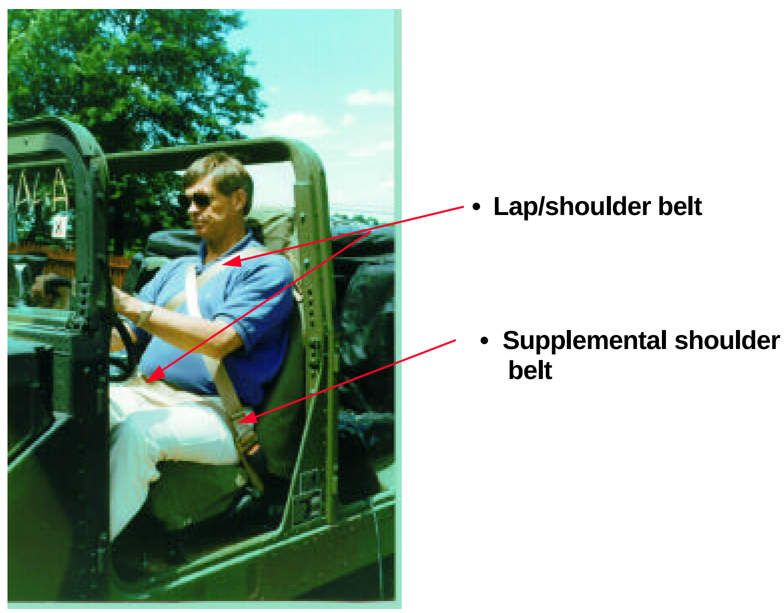

Figure 12

Based on this testing of the first mockup, it was concluded that a second mockup was needed to incorporate lessons learned in testing. These lessons included higher seat back height for additional roll over protection and head restraint for the +95th percentile male and modified side bolsters to better accommodate soldier-worn equipment and speed egress. A detailed description of the second system, called the Common Crashworthy Occupant Protection System (CCOPS) follows (note: this description approximates ARCCA's patent application for CCOPS). On the following page, Figure 21 is a perspective view of the interior of a vehicle showing a CCOPS system. Figure 22 is a side view of the CCOPS system. Figure 23 is an exploded perspective view of a CCOPS seat bottom of the system. *The system is patent pending*.

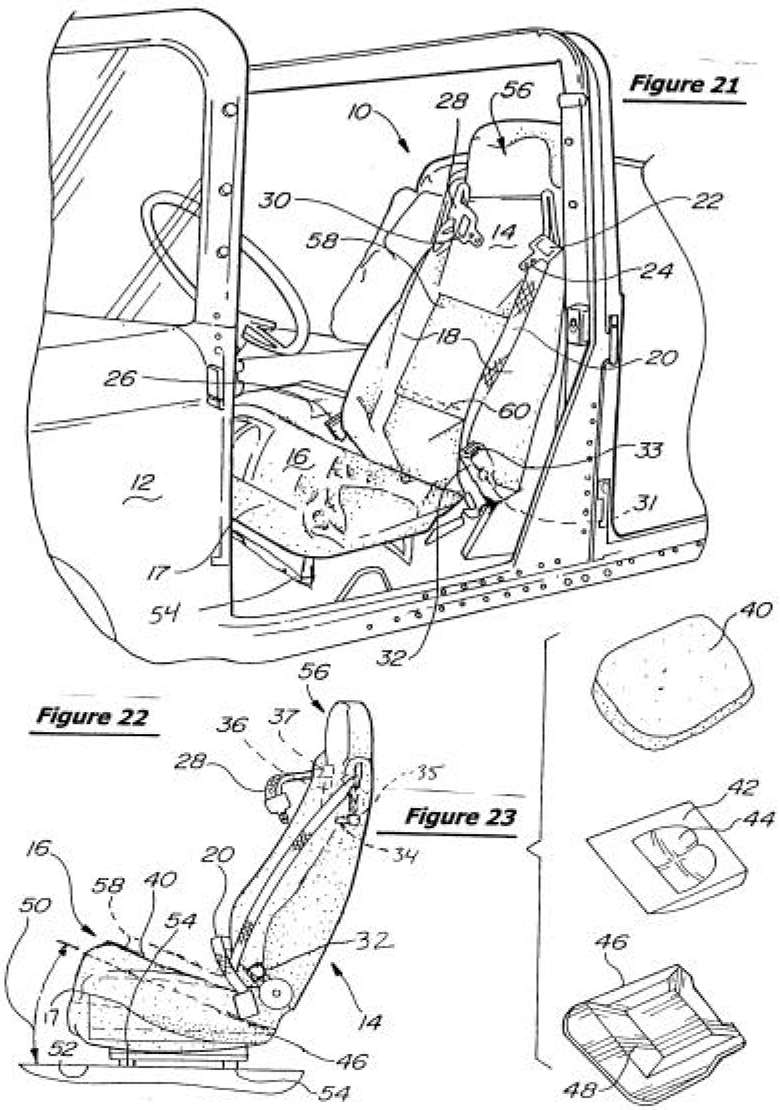

Figure 21

Figure 22

Figure 23

CCOPS is a crash protection system for protecting an occupant from injury. It includes a seat assembly having a seat back and a seat bottom, a pair of side bolsters on each side of the seat back, a combined seat/lap belt and shoulder belt restraint affixed directly to the seat assembly and a secondary shoulder restraint affixed to the seat assembly. The seat bottom includes a front portion and a ramp upwardly sloped towards the front portion of the seat bottom. The seat cushion is constructed of a rate sensitive compression material having a compressive response to a slow application of force and a rigid response to a rapid application of force. Pretensioning devices were added to both the combined seat/lap belt and shoulder belt restraint and to the supplemental shoulder belt restraint. They activate in response to a signal from a crash sensor to remove slack from the combined seat/lap belt and shoulder belt restraint and/or the supplemental shoulder belt restraint in all crashes with significant severity.

The numbers in this description refer to the corresponding illustrations in the figures. Item (10) is the CCOPS system and can be installed as a unit into a vehicle in either a front or rear seat location. The CCOPS system (10) includes a seat back (14) and a seat bottom (16). A bolster (18) on each side of the seat back (14) provides passive lateral support to the occupant. The bolsters (18) are designed to supplement the lateral restraint provided by a combined seat/lap and shoulder restraint assembly (20) and supplemental shoulder belt (28). This reduces the excursion of the occupant from the seat in collisions where the principal direction of force is directed from the sides of the occupant of the seat assembly (10). The bolsters (18) are an integral component of the seat back (14) and are of a resilient material, such as foam rubber, over a rigid metal or polymeric frame. CCOPS includes a conventional seat or lap/shoulder belt restraint (20) that is connected to a pretensioner device (34) within the seat back (14). The lap/shoulder belt restraint is a woven material (webbing). The lap portion of the lap/shoulder belt harness (20) is attached to the seat assembly (10 near the union of the seat back (14 and the seat bottom (16). This location assists in the control of the angulation of the buttocks of the occupant during unloading events during a crash. Attachment of the lap portion of the combined lap/shoulder belt restraint in this manner also improves the occupant crash protection during the roof impact portion of a vehicle roll over by minimizing occupant travel towards the vehicle roof. The lap/shoulder belt restraint (20) is stowed in a retractor/spool assembly (35) mounted to one side of the seat back (14) at shoulder level. The other end of the lap/shoulder belt restraint (20) is anchored to the side of the seat bottom (16) near the intersection of the seat back ((14) and the seat bottom ((16) and on the same side of CCOPS as the lap/shoulder belt restraint retractor (35). The combined lap/shoulder belt restraint (20) includes a cinching latchplate (22) attached the belt webbing. The latchplate (22) slides along the webbing to provide for adjustment of the length of the lap/shoulder belt restraint (20). A metal tongue portion (24) of the latchplate (22) is inserted in a buckle receptacle (26) located on the opposite side of the seat bottom (16) near the intersection of the seat back (14) and the seat bottom (16). The cinching latchplate (22) maintains the tension of the combined lap/shoulder belt restraint (20) tightly against the occupant and prevents slack from the shoulder belt portion of the combined lap/shoulder belt restraint (20) from causing the lap portion of the harness (20) to become slack during a crash. This slack would degrade the pelvic restraint provided by the lap belt portion of the lap/shoulder belt restraint (20). Additionally, while the cinching latchplate (22) helps maintain tension and prevents the lap portion from becoming slack, it also allows the pretensioner (34) to further tighten the lap portion of the lap/shoulder belt restraint (20) through the cinching latchplate (22).

The supplemental shoulder belt restraint (28) is enclosed in a retractor/spool assembly (37) on the side of the seat back (14) opposite the retractor (35) for the combined lap/shoulder belt restraint (20). A latchplate (30) is affixed to a free end of the supplemental shoulder belt restraint. The latchplate (30) is received and retained in a buckle (32) on the side of the seat bottom (16) opposite the side of the seat back (14). The buckle (32) is near the intersection of the seat bottom (16) and the seat back (14). The buckle (32) incorporates an internal lock that maintains a latch pawl (not shown) against the inserted latchplate (30). The latch pawl prevents the movement and possible disengagement of the latchplate (30) from inertial loads applied to the latch pawl when the buckle (32) is accelerated in a crash. The buckle (32) also incorporates a shield about a push button release (33) to prevent inadvertent depression of the button (33) and release of the latchplate (30).

Anchoring the restraints (20, 28) to the seat assembly (10) rather than to the vehicle (12) structure maintains the optimum geometry in the restraint harnesses (20, 28) regardless of the seat assembly (10) position. This also helps to optimize the fit of the restraints (20, 28) to accommodate the full range of occupant sizes. The anchor locations provide symmetry to the occupant in the fore and aft plane. The use of both the combined lap/shoulder belt restraint (20) and the supplemental shoulder belt restraint (28) improves the restraint effectiveness in all crash modes. It reduces body excursion for all crashes and distributes the restraint loads over a wider area of the occupant's body, thus decreasing the potential for injury from any part of the restraint. The design also permits the occupant to wear the familiar lap/shoulder belt restraint (20) and also provides vastly improved occupant protection with the addition of the supplemental shoulder belt restraint (28). Research into occupant compliance shows that an occupant may be inclined to use only the supplemental shoulder belt restraint (28) alone rather than in combination with the lap/shoulder belt restraint (20). Accordingly, CCOPS incorporates a "lock-out" to prevent occupants from engaging the supplemental shoulder belt restraint (28) until they engage the lap/shoulder belt restraint (20). Engagement means that the supplemental shoulder belt restraint (28) cannot be used until the occupant buckles the lap/shoulder belt restraint (20) to the buckle (26). The system (10) incorporates a lock-out feature that prevents the supplemental shoulder belt restraint (28) from being pulled from the retractor (37) and buckled without first attaching the lap/shoulder belt restraint (20). A small solenoid device (39) located in the shoulder belt retractor/spool assembly (37) locks the spool. When the occupant buckles the lap/shoulder belt restraint (20), a signal causes the solenoid (39) to retract and allows the supplemental shoulder belt retractor/spool (37) to operate normally. The supplemental shoulder belt retractor/spool (37) will operate normally until the lap/shoulder belt restraint (20) is unbuckled. After the lap/shoulder belt restraint (20) is unbuckled, the supplemental shoulder belt retractor/spool (37) will only allow the webbing of the supplemental shoulder belt restraint (28) to retract. A switch (31) in the buckle (32) for the lap/shoulder belt restraint (20) controls the solenoid. The switch (31) is closed when the lap/shoulder belt restraint latchplate (30) is inserted into the buckle (32). This activates the solenoid (39), unlocking the retractor/spool assembly (37) for the supplemental shoulder belt restraint (28). This allows the occupant to extract the supplemental shoulder belt restraint (28) from the retractor/spool assembly (37) and buckle.

The pretensioner devices (34, 36) each tighten either the combined lap/shoulder belt restraint (20) and/or the supplemental shoulder belt restraint (28), respectively, in the event of a crash. The pretensioner devices (34, 36) are pyrotechnic devices. Upon receipt of a signal from a crash sensor, the pretensioners cause the retractors (35, 37) to retract the lap/shoulder belt restraint and the supplemental shoulder belt restraint webbing to remove any slack from these two restraints placing them under tension. The pretensioning of the restraints (20, 28) ensures that the occupant loads the lap/shoulder belt restraint (20) and supplemental shoulder belt restraint (28) earlier in a crash. The occupant begins to decelerate with the vehicle thus minimizing the acceleration and the loads applied to the occupant. The pretensioners (34, 36) have their own secondary locking mechanism that provides a backup to the primary locking device on the retractor/spool assemblies (35, 37). When the pretensioners (34, 36) are initiated, a small pyrotechnic fires, pulling a cable attached to the retractor/spool assemblies (35, 37). This rotates the spool in the direction that retracts webbing of the belts (20, 28) onto the spool tightening the belts (20, 28). As the spool turns, spring loaded pawls engage teeth on a retractor/spool axle. The pretensioner cable remains taut by a latch or cable clamp that prevents the cable from moving in the opposite direction. This mechanism ensures that the pawls of the secondary locking device permanently remain engaged. The seat belts (20, 28) remain locked throughout the entire crash sequence including multiple impacts, rollovers, and rebound. This method of pretensioning the seat belts minimizes the potential for the retractors (35, 37) to "skip lock" by providing a built-in backup to the primary locking system. "Skip lock" is a phenomenon that occurs when the lock bar for the retractor engages the tip of a sprocket tooth rather than its root as it is intended to do. When this failure occurs, the retractor fails to function properly, leaving slack in the restraint system and degrading occupant protection.

The seat bottom (16) incorporates a seat ramp and a rate dependent compressible material that controls the pelvic motion of the occupant during frontal crashes and vertical exposures where the force vector comes from the bottom of the seat assembly (10). By incorporating a seat ramp, the phenomenon known as submarining, which occurs when poor seat belt geometry allows the pelvis of the occupant to rotate under the lap belt during a frontal crash, can be substantially reduced if not eliminated. If submarining occurs, the occupant can sustain abdominal and lumbar spinal injuries from the lap belt loading the soft abdominal region instead of the structurally strong pelvis and the shoulder belt may impinge upon the neck of the occupant resulting in central nervous system injuries. CCOPS reduces or eliminates this effect by incorporating a ramp (48) into a seat pan (46) made of a structural material such as a metal or a polymer. An intermediate resilient layer (42) adjacent to the seat pan (46) will provide support to the occupant. The intermediate resilient layer (42) can also include a contour (44) that is adapted to conform to the buttocks of a seat occupant. A rate sensitive cushion layer (40) is then disposed over the intermediate resilient layer (42). The rate sensitive cushion layer (40) has a rate sensitive compression characteristic that presents a compressive response to a slow application of force and a rigid response to a rapid application of force such as the force applied to the top rate sensitive cushion layer (40) during an impact. The intermediate resilient layer (42) is made of moldable rigid foam that provides a firm and stable surface for the rate sensitive cushion layer (40). The ramped seat bottom is (16) at an angle (50) relative to the floor (52) of the vehicle (12).

The rate sensitive cushion layer (40) covers a contoured seat bucket or the intermediate resilient layer (42). The seat contour (44) ensures that substantially all loading of the upward forces transmitted to the CCOPS occupant is done by way of the rate sensitive cushion layer (40). These foams protect the occupant from vertical loading by reducing dynamic amplification. Dynamic amplification occurs when a vehicle begins to rapidly decelerate or accelerate but the occupant's velocity remains unchanged for some time period thereafter. This delay in the occupant's deceleration develops a relative velocity between the occupant and the vehicle. When the occupant's body finally comes in contact with the vehicle, the relative velocity results in the occupant being rapidly accelerated to the same velocity as the vehicle. This acceleration is much greater than the acceleration applied to the vehicle. Had the occupant decelerated with the vehicle (i.e., remained coupled to the vehicle by an efficient seat and restraint system) the acceleration and the resultant forces applied to the occupant would not have been amplified. They are open celled polyurethane foams having a rate sensitive property providing them with high energy absorbing properties. They exhibit low compression set for their low rebound, highly damped properties. When the rate sensitive cushion layer (40) is formed of such a rate sensitive material, it retains the shape of a depressing object when it returns to its original height if it is deformed slowly. Additionally, it softens when exposed to body temperature for a period of time. Both of these characteristics cause it to conform closely to the shape of the occupant of the seat assembly (10). This conformability allows the rate sensitive cushion layer (40) to distribute the weight of the occupant and transmit force of an impact more evenly.

The rate sensitive cushion layer (40) can be formed of a foam having a variable modulus of elasticity. For example, the rate sensitive cushion layer (40) can be formed of a foam material wherein the variable modulus of elasticity is a dual modulus of elasticity. Similar ramped seat designs are disclosed in United States Patent No. 5,553,924 to Cantor et al.

CCOPS further includes supports (54) underneath the seat bottom (16) for mounting the seat assembly (10) to the floor (52) of the vehicle (12). The supports (54) can include fore and aft seat adjusters that allow the seat assembly to be moved in the fore and aft plane. The seat back (14) includes an integral head restraint or headrest portion (56) to provide back support and head restraint for the vehicle occupant. The head restraint portion (56) of the seat back (14) is aligned and contoured to ensure that the head restraint portion (56) is close to the occupant's head. This prevents significant relative motion between the occupant's head and the head restraint portion (56). Additionally, the inherent height of the head restraint portion (56) and the structural strength of the seat back (14) also provide supplemental protection from roof crush intrusion.

CCOPS can also include a seat bottom-elevating member (58) in a recess in the seat back (14), which is a deployable belt-positioning booster integrated into the lumbar section of the seat back (14). It can be rotated about an integral hinge (60) from a stowed position as shown in Figure (21) to a deployed position as shown in Figure (22). In the extended position as shown in Figure (22), the seat bottom elevating member (58) provides a platform for small adults that allows them to be positioned for maximum protective benefits from CCOPS. The seat bottom-elevating member (58) can also incorporate a seat ramp similar to the seat bottom ramp described above to limit submarining of the occupant. It is constructed of a rate or dependent urethane foam to limit the vertical displacement of the occupant during a crash that could result in submarining under the lap belt or dynamic amplification of accelerations and loads.

The pretensioners (34, 36) are connected to a sensor (or sensors) that can detect frontal, lateral, rear, roll over and slam down crashes. The pretensioners (34,36) will be initiated in all of these crash modes when the acceleration is above a predetermined threshold and the belt is in use. The sensing system is activated when the latchplate (30) for the lap/shoulder belt restraint (20) is inserted and latched in its buckle. The sensing system and switch (31) in each buckle (32) control the firing circuit for each pretensioner (34, 36). The switch (31) in the lap/shoulder belt buckle (32) and supplemental shoulder belt pretensioner activates the sensing system and partially closes the firing circuit for the lap/shoulder belt restraint pretensioner (34) and for the supplemental shoulder belt pretensioner (36). Two conditions must be satisfied to fire the pretensioners (34, 36). The pretensioner for each belt fires if (1) the belt's latchplate is latched in its buckle and (2) the sensing system is activated (the option may exist for deactivating the system for traversing rough terrain).

IMPORTANT FINDINGS AND CONCLUSIONS

Continuing to apply the Risk Management approach systematically will reinforce the need to heighten efforts to save soldiers lives. A strong partnership between the Army Safety Center and TACOM, with NAC as the proponent will contribute to a more systematic application of the process.

Army Safety Center Database. This database is understandably aimed more at mishap cause and prevention than at crash hazard mitigation. If the ASC mishap reporting system supported additional information that would contribute to crashworthiness analysis, the Army could use it to set its requirements, just as it does in Army aviation.

Federal Motor Vehicle Safety Standards. Through this analysis, experts at ARCCA agree that Federal Motor Vehicle Safety Standards (FMVSS) are woefully inadequate to ensure tactical vehicle crashworthiness. Even with the rudimentary crashworthiness data we were able to derive from our mishap analysis, this analysis demonstrated that FMVSS will not provide an adequate degree of HMMWV occupant safety.

Restraint Use. It was difficult to accurately determine restraint use. The soldier interviews indicated that, while most claim to use restraints during on-road operations, many do not use them during off-road or tactical operations. This apparently comes from an incorrect perception that restraints will prevent quick egress in emergency or live-fire situations. While we found no egress standards in the ORDs, our own human factors testing indicated that even with CCOPS, with both lap/shoulder and supplemental belts in place, an operator wearing full LBE can release the belts and leave the HMMWV in 3 to 4 seconds.

Systems Approach to Occupant Protection. The Army should take a systems approach to ground vehicle crashworthiness as it does with aviation. Too often, solutions are applied to offset an identified problem without evaluating their overall effect on occupant protection. Considerations such as radio size and positioning, gun turret location, belt geometry, ballistic protection, roof crush, comfortability, ingress/egress, restraint loading, etc. all need to be taken into account from a systemic perspective

IMPLICATIONS FOR FURTHER RESEARCH

- Determine which FMVSS are applicable and where a new standard may be required for military applications.
- There are questions related to the performance of seats under different vertical acceleration-time profiles. Work being done by the TARDEC Survivability Technology Area's Tactical Vehicle Team is expected to shed light on this issue.
- Rollovers were addressed in this analysis but are so dangerous and deadly that they also require special emphasis in this report. Work being done by armies of other nations (i.e., Australia, Israel, UK, and Austria) is well ahead of any efforts we were able to identify in the U.S. Army. These efforts were briefed at the SAE Military Vehicle Safety TOPTEC. It is recommended that TACOM partner with one or more of these organizations responsible for these efforts, especially Australia.
- US Army tactical vehicles afford little protection to side-facing occupants. This effort was limited to forward-facing seats in the HMMWV. We know from experience that side-facing seats, such as those found in the cargo compartment of most Army wheeled vehicles, are totally unsafe. Even with restraints, severe injury and fatalities are likely in many crashes.
- 21st Century Truck Program. This NAC sponsored program may be an ideal platform to apply a systems approach to occupant safety and to demonstrate life saving technologies.

REFERENCES AND ACKNOWLEDGEMENTS

Scientific & Technical Reports Summary Final Report, Contract DAAE07-98-C-L003, CDRL A001, "Test and Evaluation of an Integrated Seat System for the HMMWV," 29 JUNE 1999.

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