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Occupant Protection from Cargo in Armored Vehicles

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ABSTRACT

Inadequately restrained cargo is a problem in a wide range of vehicles, from passenger cars to heavy trucks. In a crash, the force needed to restrain the cargo is many times the weight of the cargo itself. In a passenger vehicle this means that the barrier between the cargo and the occupants must be capable of preventing the cargo from entering the passenger compartment. In heavy trucks, cargo restraints are generally used to prevent the shifting of cargo that could affect the stability of the truck and to keep the cargo on, or in, the truck during normal driving maneuvers.

A somewhat unique problem occurs in the armored security vehicle. These vehicles are often used to transport very heavy, dense, valuable cargo. More specifically, this cargo is often coin and/or boxes containing paper currency. In many cases this cargo, which may exceed 2268 kilograms (5000 pounds), is carried in the same compartment as personnel. Without a restraint or barrier capable of withstanding the loads generated by this cargo, occupants are placed at risk of serious injury from this shifting payload, especially during crash events. In order to protect these occupants, the cargo restraint or barrier must be able to prevent the cargo from entering the occupant's space and not allow the components of the vehicle or the barrier itself from loading the occupant during foreseeable crash events.

The capability of one type of cargo restraint used in these vehicles was analyzed and tested in a 30 mph frontal barrier test and found to be inadequate to prevent cargo from moving into the occupant's space. Alternative cargo restraints and barriers were considered and analyzed. One design was selected and a prototype was fabricated and tested in a simulated frontal 30 mph crash on a horizontal accelerator (sled) with the same cargo as was used in the first test. This improved design remained in place and kept the cargo away from the occupant's space and thereby would have prevented any injury to the occupant from the cargo. This program demonstrates the type of cargo barrier needed to restrain dense cargos, such as coins, and protect personnel from injury due to shifting cargo. These concepts have application in all types of vehicles.

INTRODUCTION

The problem of unrestrained or inadequately restrained cargo is a problem in many types of vehicles which has been known for years. [1] If not adequately restrained, cargo can shift during vehicle maneuvering, braking or a crash. While minor shifting can occur without creating any problems, there have been many instances where cargo has caused or increased the severity of injuries to vehicle occupants. [2] In order to protect occupants, either the cargo must be held in place or if unsecured, it must be prevented from entering the occupant's space. [3]

While there are some minimal standards regarding the need and requirements for cargo restraint in passenger vehicles, they are very limited in scope. [4, 5] In general, these standards only address relatively light cargo such as typically seen in passenger vehicles. In heavy trucks, cargo restraints are generally used to prevent the shifting of cargo that could affect the stability of the truck and to keep the cargo on, or in, the truck during normal driving maneuvers. [6, 7] However, good engineering design practices require that adequate cargo restraint should be provided to prevent shifting cargo from causing injury in the range of normal daily incidents, including foreseeable and otherwise survivable crash events.

Some examples of cargo and the means provided to prevent interaction of vehicle occupants and cargo include:

- Items in the trunk of a passenger vehicle are separated from the occupant's space by a bulkhead or, in some cases the rear seatback.
- Items in the rear cargo area of a van, station wagon or SUV are separated from the occupant's space by the occupant's seatback.

- Cargo in some utility vans maybe separated from the occupant's space by a cargo barrier.
- Spare tires are bolted to the vehicle to keep them in their stowed position.

In some cases these methods of cargo retention are capable of preventing cargo from interacting with the vehicle's occupants, however in some cases they have proven to be inadequate. There have been several incidents where cargo in the trunk of a vehicle has deformed or broken the rear seat of a vehicle and either entered the passenger compartment or caused the deformed or broken seatback to load an occupant. If allowed to enter the occupant's space, it could cause injury either through direct loading into the occupant or by causing increased belt loads on a restrained occupant. Additionally there have been instances where the means used to secure an item, such as a spare tire have failed, allowing the item to move freely with the potential to interact with vehicle occupants. Obviously the ability to resist loads from cargo must increases with the mass of the cargo; therefore this issue is only made worse as the mass of the cargo increases. Additionally, the heavier the cargo, the higher the forces are that an occupant could be subjected to if the cargo is allowed to enter the occupant's space. One instance where potentially heavy cargo is being transported, armored route vehicles, will be the focus of this paper.

A somewhat unique problem occurs in these armored vehicles. These vehicles are often used to transport very heavy, dense, valuable cargo. More specifically, this cargo is often coin and/or boxes containing paper currency. In many cases, this cargo is currently carried in the same compartment as personnel and may exceed 5000 pounds. Without a restraint or barrier capable of withstanding the loads generated by this cargo, occupants are placed at risk of serious injury from this shifting payload, especially during crash events. In order to protect these occupants, the cargo restraint or barrier must be able to prevent the cargo from entering the occupant's space and not allow the components of the vehicle or the barrier itself from loading the occupant during foreseeable crash events.

CURRENT DESIGN

Armored vehicles used on transport routes vary widely in design and size from heavy trucks to cargo vans similar in size to a standard 12-passenger van. The analysis in the paper will focus on the smaller, more common vehicles in this group used for making deliveries and pickups at banks and stores. In many of these vehicles there is an occupant, or messenger, seat in the rear cargo compartment of the vehicle as seen in Figure 1.

Figure 1. Armored Van Cargo Compartment Looking Forward with the Messenger Seat Shown

In many cases, the seat is the only separation between an occupant and the cargo. As previously mentioned this cargo can be very heavy and dense. In the case of coins, they are usually transported in one of two ways, bagged or boxed. Boxes of coins vary in weight depending on value and type of coin. In the United States, there are four main coin boxes. The value and weight of a standard box of each is shown in Table 1.

	Value (US Dollars)	Weight Kg (Pounds)
Pennies	$25	6.9 (15.2)
Nickels	$100	10.1 (22.3)
Dimes	$250	5.8 (12.7)
Quarters	$500	11.6 (25.5)

Table 1. Coin Box Weight

DESIGN REQUIREMENTS

In general there are several factors that need to be considered in the design of a system to prevent interaction of the armored route van's cargo and its occupants. First is the means to be used to prevent the cargo from shifting. Cargo can either be secured in the cargo area using cargo tie downs, stored in a cabinet or rack type system, or separated from the occupant by a bulkhead style barrier. Since these vehicles are used to make deliveries and pickups at several locations every day, use of a tie down system would require the messenger to re-secure the load after every stop, increasing workload, time required, and the potential for error. While use of a cabinet or rack system is certainly feasible, some fleet operators desire not to limit the utility or flexibility of their vehicles by installing this type of system. The third option is separation of the occupant from the cargo by using a barrier. While a barrier can slightly reduce the available cargo space, it can also be a very effective means of preventing a wide variety of cargo from coming into contact with an occupant when properly designed.

The second factor that must be considered in designing a cargo restraint system is the mass of the cargo that must be restrained. While the total mass of the cargo being transported in an armored route van can vary widely, generally there is an upper limit determiner either by the vehicle converter or by the base vehicle's manufacturer's gross vehicle weight rating (GVWR). This defines the upper limit of the payload mass that can be carried and should be considered in the design of the cargo barrier.

The third factor is the severity of the event for which cargo restraint is required to be effective. This severity should be selected based upon what is known about the types of incident the vehicle may be subjected to. Since this system is expected to prevent an increase in severity of occupant injury in a crash, it should be capable of preventing the cargo from loading the occupant in a crash that is otherwise considered protectable with a well-designed occupant restraint system. At a minimum, the cargo restraint system should be capable of keeping the cargo from contacting an occupant in at least a 48 KPH (30 mph) frontal impact as required by FMVSS 208.

When combined, these three factors provide the minimum capability needed to prevent shifting cargo from interacting with occupants.

ANALYSIS OF CURRENT SYSTEM

At the beginning of this program, a used 1995 armored route van was acquired and the provided cargo securing method was analyzed. In the van analyzed, the only means provided to prevent the motion of the cargo was a 25.4 by 50.8 millimeter (one-inch by two-inch) hollow rectangular tube, with a 1.6 mm (0.0625 inch) wall thickness, across the cargo area on the floor as shown in figure 2. According to the van's converter, the maximum payload this van is intended to carry was 363 kilogram (800 pounds), in a maximum of 30 boxes placed against the cargo bar all the way across the cargo area as seen in figure 3. This placement of the cargo is an important factor in the design of the barrier. [1] With the cargo against the barrier, there is no opportunity for the cargo to develop relative velocity to the barrier in a crash. This relative velocity would increase the forces the cargo places on the barrier in a crash and generally increases as the initial distance between the barrier and the cargo increases. Using the specifications of the vehicle's converter and the mass of the common coin boxes, these limits would allow the van to carry a maximum of 30 boxes of quarters with a total mass of 347 kilograms (765 pounds).

Figure 2. Armored Van Cargo Bar
View Looking Aft From Messenger's Seat

Figure 3. Armored Van Payload
View Looking Forward

In order to evaluate the potential capability of this means provided to securing these coin boxes, some basic beam loading calculations using accepted engineering formulas [8] were performed. The beam was assumed to be simply supported with an evenly distributed load over the 864 mm (34 inch) total length. Based on these calculations, it was determined that, as designed, the cargo retention bar would only be capable of carrying 4225 Newtons (950 pounds) of load before failing. This equates to approximately 1½ boxes of quarters in a 48 kph (30 mph), 25 G frontal impact. With the cargo restraint design, provided as standard in this armored route van, the cargo restraint bar would be capable of preventing the load from shifting during braking but the allowable cargo would cause the bar to fail in all but the most minor of crashes.

As a comparison, the beam calculation was repeated using a solid bar with the same external dimensions as the provided hollow tube. The calculations indicated that the solid cargo retention bar would only be capable of carrying 11.3 kilonewtons (2548 pounds) of load before failing. This equates to approximately 4 boxes of quarters in a 48 kph (30 mph) frontal impact, again only adequate to prevent loss of cargo restraint during braking and minor impacts.

These calculations showed that the use of a 25.4 by 50.8 millimeter (one-inch by two-inch) cargo retention bar is severely under designed and would be incapable of preventing the cargo from contacting the messenger's seat located in the cargo compartment. Since the messenger's seat is a standard van seat, it was known from prior work in analyzing automotive seatbacks that the seat would also be incapable of resisting the loads that would be generated if the cargo were to impact the rear of the seat. Additionally, the two-inch height of the bar would allow cargo to pass over the bar if it was stacked more that one box high or to rise off the vehicle floor in a crash. With these shortcomings it was expected that the cargo bar would fail in a 48 KPH (30 mph) frontal impact.

CRASH TEST

To confirm the calculation and further investigate the performance of the provided system a 48 KPH (30 mph) frontal barrier impact test was conducted with the armored route van. For this test the vehicle was loaded with 15,000 dollars or 347 kilograms (765 pounds) of quarters in 30 boxes as seen in Figure 3. The messenger seat was removed from the van for this test so as to be conserved for the full cargo barrier design test to be conducted later.

The crash pulse shape from this test was somewhat unusual in that at a point approximately 13 milliseconds into the crash, the frame accelerometers show that the vehicle is actually being accelerated into the barrier and the vehicle's speed is increasing. This is a rather unusual result until one considers the sizeable movable mass of the cargo. Review of the video demonstrated that this acceleration of the vehicle into the barrier is likely the result of the cargo impacting the interior of the van, driving the van forward into the barrier. This unusual pulse shape is seen in figure 4. The authors have conducted other crash test in which there was a large shifting mass where similar acceleration-time characteristics have been seen.

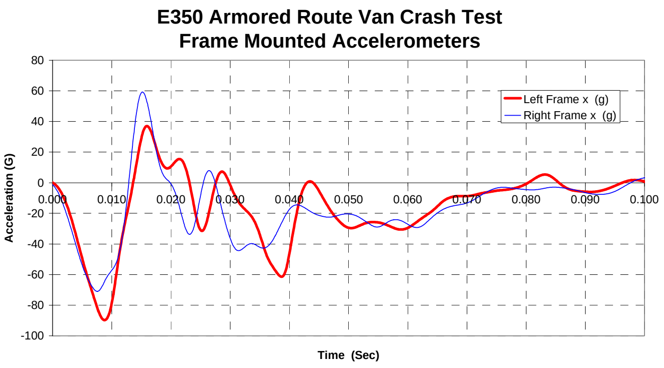

Figure 4. Longitudinal Van Frame Crash Pulse

This unusual pulse shape was not seen on the accelerometer mounted on the van body's cross members. Due to a problem which occurred during the test, data from the left cross member was not useable, therefore only the data from the right cross member is presented here. The cross member acceleration data is superimposed with the frame accelerations in figure 5. It is this right cross member data that best represents the overall vehicle acceleration which occurred in this test.

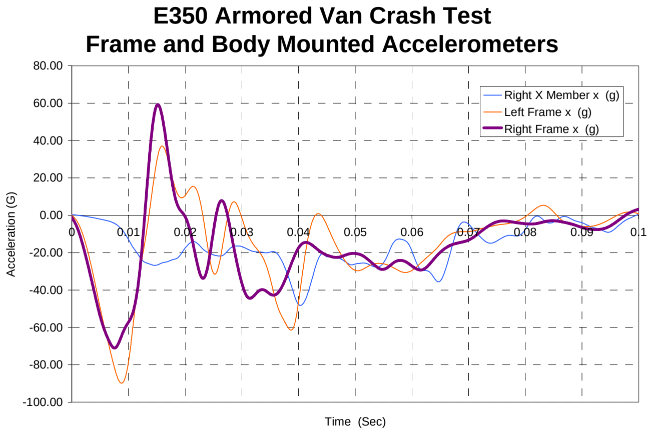

Figure 5. Longitudinal Van Crash Pulse

Cross member acceleration data shows that the impact of the van into the barrier resulted in an instantaneous peak longitudinal vehicle acceleration of 48 G's and a total pulse duration of approximately 80 milliseconds. While the instantaneous peak acceleration measured on the vehicles cross member was 48 Gs, this is not the effective acceleration experienced in this crash it is a peak or maximum value which has no finite duration. For an acceleration to truly have an effect on the loads experienced, it must be maintained for some duration. Opinions on how long of a duration is required for an acceleration to truly have an effect are varied. For evaluation of the potential for injury to an occupant, it is generally accepted that an ATD response acceleration with very short durations have no effect and will not cause injury to a human. Eiband applied this approach to his analysis of human tolerance in the 1950's. [9] For his analysis, Eiband simplified the input acceleration pulse to a trapezoid and measured the duration of the magnitude of the trapezoid. In a frontal impact, such as this armored route van test, Eiband's non-injurious acceleration level of 44 Gs is applicable for durations up to 40 milliseconds. It is for similar reasons that FMVSS 208 applies a 3 millisecond clip for the limit on chest response acceleration.

Many non-biological materials exhibit similar behaviors in that they can carry loads beyond their accepted or anticipated strength so long as the duration that load is applied is very short. This is likely related to the very small amount of work done or energy transferred when loads are applied for only a short duration. For this reason one must look at the effective sustained acceleration, not just the peak acceleration. This issue has been addressed by the US Navy when accessing the performance of aircrew escape systems. The Navy's approach to deal with very short transient acceleration which exist post-filtering is to apply a 10 millisecond moving average to the data. [10] The peak value of this calculation is the effective peak or sustained acceleration of the data and is to be used in evaluating the values in relation to performance standards. In doing this for the crash pulse of the armored route van, the effective sustained acceleration is approximately 32.0 Gs. The change in velocity for the van during this impact was 54.6 kph (33.9 mph) which is consistent with the 48.9 kph (30.4) mph approach speed and the minimal rebound away from the barrier.

During this crash the coin boxes loaded the cargo bar causing it to bend and separate from the attachment on the left side prior to releasing on the right side. This allowed the coin boxes to move forward, through the area normally occupied by the messenger's seat and messenger and impact the forward bulkhead that separates the cargo area from the driver's compartment. The motion of the cargo during the impact is shown in figure 6 with the post-test cargo position shown in Figure 7.

Figure 6. Crash Test Cargo Motion
View looking down, forward to the left

Figure 7. Post-Crash Cargo Position with Cargo Shifted Forward in Van

IMPROVED CARGO BARRIER DESIGN

In order to protect the messenger from the cargo that must be transported, substantial improvements had to be made to the cargo barrier. The improved design was developed to meet the transport specification identified by the van's converter. For this vehicle it was required to transport of up to 800 pounds of coin in up to 30 boxes, placed in one layer on the floor with the most forward row of boxes placed against the barrier. Given the 34 inch span across the cargo area of this vehicle, and using a 25 G sustained acceleration as a minimum design, required that the bar at the base of the cargo barrier be a minimum of a 50.8 mm by 101.6 mm (two inch by four inch) hollow rectangular tube with a 6.4 mm (¼ inch) wall thickness. Additionally, the cargo bar was bolted to the frame rails of the vehicle and attached to the floor to increase the strength over the pin design seen in the actual armored route van. It was also determined that additional structure needed to be added to prevent the cargo from passing over this low barrier. While this upper portion of the barrier needs to be capable of preventing cargo from entering the area occupied by personnel, the bottom portion of the barrier will carry the largest portion of the forces generated by the cargo. It was determined that a standard, off the shelf cargo barrier manufactured for vans would be adequate to prevent cargo from passing over the lower barrier with only minor reinforcement. In order to test this design, a prototype was fabricated; using an exemplar van cargo box, to match the dimensions present in the crash tested armored route van. This prototype was then subjected to a horizontal accelerator test to verify the ability of the design to maintain the cargo away from the occupant.

IMPROVED CARGO BARRIER DESIGN SLED TEST

In order to verify the improved design was capable of preventing the cargo from entering the occupied areas of a route van, a simulated route van was prepared from a standard cargo van. A barrier of the improved design was mounted across the cargo area of the van, just aft of the messenger seat. The messenger seat from the actual route van was installed in this van in order to verify that the barrier not only prevented the cargo from contacting the seat, but also to make sure that the barrier itself did not load the messenger's seat.

This van, with the improved barrier installed, was then mounted on a horizontal accelerator such that the simulated impact would be a zero degree principal direction of force, or a direct frontal.

The cargo for this sled test was exactly the same as what was used in the prior crash test and was loaded in the same fashion for both tests. The pre-test cargo and barrier are shown in figure 8.

Figure 8. Pre-Sled Test Cargo Position
Looking Forward

While the goal was to test this vehicle with the same pulse as was acquired through actual barrier crash testing of the armored route van, some adjustments were made to allow for the test facility to generate the crash pulse. The basic parameters for the sled pulse are presented in Table 2 along with the values from the previous crash test.

	Effective Sustained Acceleration (G)	Velocity Kph (mph)	Duration (mSec)
Crash Test	32.0	49.1 (30.5)	83 – 100
Sled Test	32.1	56.8 (35.3)	85

Table 2 Pulse Comparison

The acceleration-time profiles for the crash and sled tests are shown in Figure 9. While the crash test has a higher peak acceleration, the sled test had a slightly higher velocity and thus a higher energy. Additionally the effective sustained acceleration in the sled test was slightly greater than in the crash test. While there were some differences between the sled and the crash tests, they are comparable for looking at the performance of the subject cargo barrier. While it is desirable to more closely control parameters, in a test, such as this one, with a large amount of moving, shifting mass, such control is difficult to achieve.

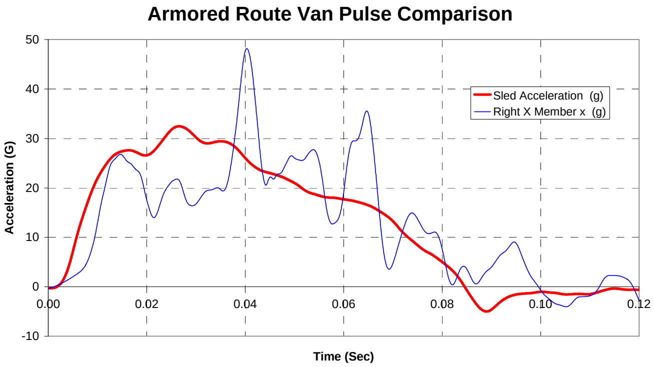

Figure 9 Sled and Crash Test Pulses

During the sled test the cargo shifted forward, loading the barrier and causing many of the boxes of coins to rupture. The motion of the cargo during this test is shown in figure 10.

Figure 10. Sled Test Cargo Motion

Following the test, the cargo barrier was still completely intact and the cargo was retained in the area behind the barrier with no cargo entering the space where the messenger's seat is located. The post-test cargo and cargo barrier is shown in figure 11 with the cargo barrier in the forward area. Figure 12 shows the area forward of the cargo barrier is free of damage and cargo did not enter this area.

Figure 11. Post-Sled Test Cargo Barrier
Looking Forward

Figure 12. Post-Sled Test Cargo Barrier

CONCLUSION

This testing demonstrated that, when properly designed and tested, a cargo barrier can be capable of preventing a very heavy, dense payload from intruding into occupied space. This redesigned cargo barrier was constructed with for less that two hundred dollars and weighed less than two hundred pounds. It is expected that actual production costs would be less. Use of such a barrier is critical to ensure that occupants of a vehicle are separated from the hazards associated with shifting cargo, both in crashes as well as everyday vehicle maneuvers and braking. While this demonstration test was associated with an armored route van, the principles apply to any vehicle. Namely, the barrier separating occupants from cargo needs to be sufficiently strong to prevent cargo from causing a failure that will allow it to enter the occupied space. In order to assure sufficient strength, design decision related to the allowable cargo mass as well as the severity of the crash must be made in order to design an adequate barrier. The barrier design should then be tested to assure that it meets the design requirements under the dynamic conditions of a crash. This approach would apply equally to large cargo barriers, such as the one in this program, as well as the bulkhead or rear seat backs in passenger vehicles. All vehicles require adequate restraint in order to prevent cargo from entering the occupant's space and increasing the risk of injury.

REFERENCES

1. Schaper, D. and Zech, G., *Cargo Retention in Passenger Cars Under Accident Conditions*, Society of Automotive Engineers, Paper Number 860206, Warendale, PA 1986.
2. Byard, R.W, Bourne, A.J. and James, R., *Childhood Deaths and Cargo Barriers in Cars*, J. Pediatric Child Health (1999) 35, 409-410.
3. Bacon, D.G.C. and Gazeley, I., *Load Restraint for the Protection of Occupants in Light Vans Including Car Derivatives*, Tenth International Technical Conference on Experimental Safety Vehicles, Oxford, England, July, 1985.
4. E/ECE/324 & E/ECE/TRANS/505 Rev. 1/Add. 16/Rev.4 Regulation 17 Annex 9.
5. Swedish Standard 2562, September 15, 1983, Issued by Swedish Standards Institute, Stockholm, Sweden.
6. Code of Federal Regulations, 49 CFR, Part 392, October 2003.
7. Code of Federal Regulations, 49 CFR, Part 393, October 2003.
8. Avallone, E. A., and Baumeister, T., III, Marks' Standard Handbook for Mechanical Engineers, Ninth Edition McGraw-Hill Book Company, 1987
9. Eiband, A.M. *Human Tolerance to Rapidly Applied Acceleration,* (NASA Memo No. 5-19-59E). Washington, DC., 1959.
10. Military Specification, System, Aircrew Automated Escape, Ejection Seat Type: General Specification For, MIL-S-18471G(AS), 8 June 1983.

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