Assessment of Retention System Effects of Level III Armored Vehicles

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Abstract: The automotive armoring industry, which protects against ballistic attacks, lacks studies regarding damage to the human body during a collision. In this work, we study the mass changes in a vehicle undergoing a level III armored process, through a numerical evaluation of the full-frontal impact of a sport utility vehicle (SUV)—a Ford Explorer 2002. In this work, we present two evaluations. We first analyze the displacement suffered by the vehicle during an impact due to the increase in mass and structural stiffness and we then evaluate the deceleration loads that the user suffers in the event of a crash. In addition, dynamic analyses were performed to quantify the head injury criterion (HIC) and chest severity index (CSI) on a 50th percentile dummy to calculate the probability of the occupant suffering possible injuries. The outcome shows a comparison between the acceleration severity index (ASI) of a commercial vehicle adapted to an armored process and an unshielded vehicle.

Keywords: biomechanics; crashworthiness; passive safety; armored

1. Introduction

The production of armored vehicles has experienced a “boom” in recent years in Mexico, with a production of 1050 units in the first half of 2017. From this, 91% were sport utility vehicles (SUVs), 7% sedans, and 2% truck tractors [1], positioning Mexico as one of the leading producers of armored vehicles in Latin America, which exports to different countries, such as Afghanistan, Iraq, Egypt, Israel, among others [2]. In recent years, international brands, such as Mercedes Benz and Audi, have manufactured these vehicles in Mexican plants [3–5]. Despite the growth of armored vehicles within the automotive industry, there are few collision records, in vehicles modified structurally, that would help one understand the safety these vehicles offer at the moment of a collision. In this work, we study the mass changes of a modified car.

However, this study has different limitations since the technical data of the structural modifications made to a vehicle after an armoring process are not available. Second, the computational processing capacity necessary to carry out a complete study is very high; therefore, this research divided the study into two parts: (1) the virtual model of the SUV...
was analyzed, and (2) the kinematic behavior of a virtual dummy was studied, using as main variables the increase of the vehicle mass and the mechanical properties of the material used in the armoring process. Finally, it is important to mention that, during a collision, there are three types of impacts, the first involves the collision of the structure of the car, the second comprises the collision of the user’s body against the vehicle’s interior, and the third collision occurs when the internal organs of the human body collide against the internal walls of the human body [8–11].

We conducted a numerical evaluation of a frontal impact of an SUV Ford Explorer 2002 with level III vehicle armor. The work was carried out under the National Highway Traffic Safety Administration (NHTSA), Federal Motor Vehicle Safety Standard (FMVSS) 208 regulation, and FMVSS 214, which specifies the boundary conditions necessary to validate the results obtained in a frontal impact. This analysis was developed using the finite element method (FEM) for dynamic analysis and integrating the shielding [6]. The methodology used was carried out through activities, such as verification of the virtual model, calculation of the acceleration severity index (ASI) of the SUV, and the armoring process. In addition, the Head Injury Criterion (HIC) and chest severity index (CSI) were obtained for a 50th percentile dummy, according to the data provided by the collision of the structurally modified vehicle.

2. Materials and Methods

This section is divided into subsections. The steps used to evaluate the passenger damage in an armored SUV level III are shown in the following list:

- Inquired about the European and American regulations related to collision tests.
- Expose theories of injury evaluation. In this case, standardized measurement systems, such as ASI and HIC, were used [12,13].
- Shielding process in the virtual model—the extra weight due to armoring process is added.
- Numerical analysis of the frontal collision of the modified vehicle using LS-DYNA® software (Canonsburg, PA, USA)—a virtual test is generated to obtain the acceleration severity index and assess the forces concentrated in the driver due to a sudden deceleration during a crash.
- Implement border conditions for the frontal collision test in the armored vehicle. A numerical crash simulation with a 50th percentile virtual dummy is generated with LS-DYNA® to obtain the dummy damage during impact on an armored vehicle.
- Results, discussions, and conclusions. The simulation of the restraint system performance (seatbelt) on a 50th percentile dummy during an impact on an armored vehicle and an unshielded vehicle. In the end, a conclusion will be presented on whether it is safe to use restraint systems, such as the seatbelt inside of an armored vehicle at the time of a collision.

2.1. Development

The FMVSS specifies the vehicle construction, design, and durability requirements. Federal rules are used for frontal collision and lateral and rear tests that contemplate three thematic axes: avoid a collision, resistance during the impact, and safety standards (activation of the retention systems). The 208 standard refers to the protection of the occupants in specific seatbelts. It specifies the requirements for test dummies in passenger SUVs, trucks, and bus vehicles, with active and passive restraint systems [14–16]. The FMVSS 214 standard establishes an impact speed of 54 km/h for frontal impact tests against non-deformable barriers [17].

In addition to the standards for crash tests, it is essential to emphasize that, during a crash, two physical concepts are presented, which help understand the behavior of the collision effects. The first concept is the energy available in the collision, representing the maximum kinetic energy by elastoplastic deformation of the vehicle and the occupants affected during an impact. The second concept is associated with the restitution phenomenon,
which associates the relative speeds of the vehicle at the beginning and end of the available energy dissipated by the structural deformation of the vehicle and the occupant [18]. Based on these standards and the physical concepts present in the collision, pertinent analyses were developed to demonstrate the restraint system safety in an armored vehicle.

2.2. Impact Analysis of the SUV

It is necessary to know the available energy that the vehicle must dissipate. For this purpose, the kinetic energy equation is used [8].

\[ E = \frac{1}{2} mv^2 \]  

(1)

where \( m \) is the mass of the car and \( v \) is the impact speed, this equation provides the total energy generated up to an instant before the collision and should be the energy to dissipate by the car structure deformation and restraint systems [19]. Therefore, the SUV Ford Explorer 2002 XLT 4WD was selected (see Figure 1), which has a mass of 2253 kg, a length of 4.81 m, a width of 1.83 m, and a height of 1.83 m [20]. This virtual model was used to perform a dynamic analysis in a frontal collision speed of 54 km/h [21]. This virtual model was created by the National Crash Analysis Center (NCAC) of the George Washington University and validated by the United States New Car Assessment Program (USNCAP). This model was developed through the process of reverse engineering, providing experimental and simulating methods, adding functional capabilities of the suspension and steering subsystems; therefore, it can be considered a suitable virtual model to perform simulations with reliable results, representing adequate energy dispersion at the moment of an impact [22]. Therefore, it is assumed that this virtual model accurately represents the real model of the SUV; however, the mass differs in this study. Therefore, entering the virtual model into the computational program will assign a specific mass according to the additional weight that comprises the armoring mass.

![Comparison of virtual SUV model and real SUV model: (a) Real model of a 2002 Ford Explorer SUV XLT 4WD [23]; (b) virtual model of the same SUV Ford Explorer 2002 XLT 4WD.](image)

Figure 1. Comparison of virtual SUV model and real SUV model: (a) Real model of a 2002 Ford Explorer SUV XLT 4WD [23]; (b) virtual model of the same SUV Ford Explorer 2002 XLT 4WD.

The engineering method of an armored vehicle is the same for all levels, with the differences in material thicknesses for each category. For the armoring process of a vehicle, ballistic materials, aramid fibers, and special glasses are used. This process adds extra weight to the vehicle, which influences the inertial energy of the system. Different levels of the armor describe the protection capacity against impacts of different calibers. The lowest levels are levels I, II, and III. These correspond to anti-assault type armor. Levels IV, V, and VI correspond to anti-kidnapping and anti-attack categories, capable of withstanding impacts of high caliber ammunition. However, this work focuses on the level III anti-assault lowest levels, because it is the most common armor among users of armored vehicles—enough to withstand frequent weapon calibers, such as 32, 38, 40, and 9 mm. In addition, it is important to note that the armoring process in level III focuses on reinforcing walls and windows and not the whole car structure; hence, the structural stiffness of the automobile
is not altered. Thus, in a car accident, the vehicle is able to hold the greatest amount of energy as a protection mechanism for the occupants [24]. Table 1 shows the characteristics of the materials used in level III anti-assault armored vehicles [10].

The AML 90 alloy contains large amounts of chromium, nickel, and molybdenum. This material combination is characterized by high strength, toughness, and ductility. Therefore, this material has a large energy absorption capacity of around 44.5 J through Charpy impact tests. This factor is not only crucial for the energy absorption of ballistic projectiles, it is also a relevant variable in the case of impact, where the ballistic material is expected to absorb kinetic energy accumulated from the system during a collision [25].

The mechanical properties of the adapted parts in a level III armored were changed for the numerical model modification. This was done in order not to alter the geometry of the numerical model and to avoid excessive use of computational processing. The principal variables were the mass increments and the mechanical properties of the materials used in the shielding process. The current model comprises piecewise linear plasticity type materials relative to elastoplastic behavior and rigid type materials, applicable to engine parts and wheels [23,26]. Table 2 shows the mass change of the SUV parts and Figure 2 shows the parts modifying the SUV model.

Table 1. Materials used for anti-assault type armoring.

| Material Properties | Ballistic Steel | AML-90 | Laminated Glass |
|--------------------|-----------------|--------|-----------------|
| Thickness (mm)      | 3.175           | 38     |                 |
| Density (kg/m³)     | 7850            | Glass = 2500 |  |
| Yield strength (MPa)| 1265            | 98     | 98.2            |
| Ultimate tensile strength (MPa) | 1337.1        |  |

Table 2. Mass change of SUV parts subjected to the armoring process.

| Part                          | Amount | Original Mass (kg) | Armoring Mass (kg) |
|-------------------------------|--------|-------------------|--------------------|
| Front door (A)                | 2      | 11.75             | 39.2               |
| Back door (B)                 | 2      | 10.14             | 34.91              |
| Rear fender (C)               | 2      | 3.29              | 16.19              |
| Rear window frame (D)         | 2      | 1.36              | 5.7                |
| Door frame (E)                | 2      | 4.49              | 19.51              |
| Upper front post (F)          | 2      | 1.34              | 4.91               |
| Lower front post (G)          | 2      | 3.11              | 10.72              |
| Door divider post (H)         | 2      | 3.87              | 12.92              |
| Trunk (I)                     | 1      | 3.61              | 30.82              |
| Awning (J)                    | 1      | 20.28             | 91.86              |
| Firewall (K)                  | 1      | 3.35              | 22.71              |
| Lateral firewall (L)          | 2      | 1.99              | 7.21               |
| Front floor (M)               | 1      | 13.6              | 58.5               |
| Central floor (N)             | 1      | 11.75             | 47.03              |
| Back floor (O)                | 1      | 8.07              | 39.21              |
| Floor lower part of the door (P)| 2  | 4.31             | 14.68              |
| Front window (Q)              | 2      | 3.73              | 35.73              |
| Back window (R)               | 2      | 2.93              | 28.41              |
| Rear wing (S)                 | 2      | 0.93              | 8.94               |
| Windshield (T)                | 1      | 11.32             | 105.69             |
| Trunk window (U)              | 2      | 3.61              | 34.63              |
| Rear window (V)               | 1      | 9.15              | 85.44              |
| Front side window             | 2      | 3.73              | 35.73              |
| Passenger side window         | 2      | 2.93              | 28.41              |
| Side mirrors                  | 2      | 0.93              | 8.94               |
| Windshield                    | 1      | 11.32             | 105.69             |
| Rear side window              | 2      | 3.61              | 34.63              |
| Rear window                   | 1      | 9.15              | 85.44              |
This study emphasizes the mass difference between an original factory vehicle and a modified armored vehicle. This additional mass will directly affect the energy available in the system during the collision, as shown in Equation (2).

\[ m_{\text{total}} = m_{\text{original}} + m_{\text{armored}} \]  

\[ m_{\text{total}} = 2253 \text{ kg} + 1255 \text{ kg} = 3508 \text{ kg} \]

Applying this result on Equation (1), the kinematic energy on the armored vehicle can be obtained, and it can be compared with the kinematic energy of the unshielded vehicle, as shown in Table 3.

Table 3. Comparison of the kinematic energy between the armored vehicle and the vehicle without armoring.

| Armored Vehicle | Vehicle without Armoring |
|-----------------|--------------------------|
| \( E_k = \frac{1}{2} (3508) (15.64)^2 \) | \( E_k = \frac{1}{2} (2253) (15.64)^2 \) |
| \( E_k = 429 \times 10^3 \text{ J} \) | \( E_k = 307 \times 10^3 \text{ J} \) |

This difference in mass shows a considerable increase in kinematic energy that must dissipate the vehicle in a crash, with an energy increase of almost 40% compared to the \( 307 \times 10^3 \text{ J} \) generated by the mass of an original factory vehicle. In this way, the momentum in both cases is quite different. Crash simulations were performed at 54 km/h in 10 milliseconds (ms) intervals to know the ASI. Table 4 shows the collision sequence in a lapse from \( t = 0 \) to \( t = 120 \text{ ms} \).

Once the dynamic simulation was obtained, it was corroborated with a public report by the George Washington University, Virginia Campus, and supported by the NCAC [21]. This report shows the acceleration and displacement behavior of the frontal part of the SUV model corresponding to the engine area during the impact. Figure 3 shows a comparison of both acceleration graphs; it is observed that they are similar and allow validating the simulations conducted in this research.

Once the impact simulation is obtained, it is essential to calculate the kinematic energy numerically. Therefore, an energy graph of the system is deployed, as shown in Figure 4. Additionally, the dummy seat graph of the deceleration is shown in Figure 5. One can see that the maximum peak is at 50 milliseconds, and regarding the displacement graph, one can see how the front part of the SUV model absorbs the kinematic energy in the system, which corresponds to the restitution phenomenon [18] (see Figure 6).
Table 4. Collision simulation of the armored SUV and unshielded SUV.

| Time (ms) | Collision Simulation from 0 to 120 ms of the Explorer 2002—without Armoring | Collision Simulation from 0 to 120 ms of the Explorer 2002—Armored | Time (ms) | Collision Simulation from 0 to 120 ms of the Explorer 2002—without Armoring | Collision Simulation from 0 to 120 ms of the Explorer 2002—Armored |
|----------|--------------------------------------------------------------------------------|------------------------------------------------------------------|----------|--------------------------------------------------------------------------------|------------------------------------------------------------------|
| 0        | ![Image](attachment:1)                                                                 | ![Image](attachment:2)                                                                 | 70       | ![Image](attachment:3)                                                                 | ![Image](attachment:4)                                                                 |
| 10       | ![Image](attachment:5)                                                                 | ![Image](attachment:6)                                                                 | 80       | ![Image](attachment:7)                                                                 | ![Image](attachment:8)                                                                 |
| 20       | ![Image](attachment:9)                                                                 | ![Image](attachment:10)                                                                | 90       | ![Image](attachment:11)                                                                 | ![Image](attachment:12)                                                                |
| 30       | ![Image](attachment:13)                                                                | ![Image](attachment:14)                                                                | 100      | ![Image](attachment:15)                                                                | ![Image](attachment:16)                                                                |
| 40       | ![Image](attachment:17)                                                                | ![Image](attachment:18)                                                                | 110      | ![Image](attachment:19)                                                                | ![Image](attachment:20)                                                                |
| 50       | ![Image](attachment:21)                                                                | ![Image](attachment:22)                                                                | 120      | ![Image](attachment:23)                                                                | ![Image](attachment:24)                                                                |
| 60       | ![Image](attachment:25)                                                                | ![Image](attachment:26)                                                                |          | ![Image](attachment:27)                                                                | ![Image](attachment:28)                                                                |

![Graph](attachment:graph.png)

Figure 3. George Washington University acceleration report of the upper part of the engine on the X-axis compared with the model of this work.
Figure 4. The kinetic energy of the armored SUV.

Figure 5. Armored SUV driver’s seat acceleration on the X-axis.

Figure 6. Displacement of the armored vehicle in the X-axis.

Figure 4 shows the energy of 428 KJ calculated numerically, similar to the analytically obtained value. This difference in energy obtained is generated due to the decimals used analytically and those used by the software. However, the difference between both calcula-
tions is despicable, so the numerical value will be taken to calculate the ASI. Equation (3), related to energy dissipation, shows the impact force of the system.

\[ F = \frac{E_d}{d} = \frac{428 \times 10^3 \text{ J}}{0.42 \text{ m}} = 1017.04 \times 10^3 \text{ N} \]  

(3)

With the displacement graph and the armored vehicle speed behavior graph, the ASI number of the vehicle can be obtained, which will show whether the vehicle is safe or not. Equation (4) describes the acceleration limit in the armored SUV.

\[ \ddot{a}_x = \frac{F}{m} = \frac{1017.04 \times 10^3 \text{ N}}{3508 \text{ kg}} = \frac{208.92 \text{ m/s}^2}{3508 \text{ kg}} = 29.58 \text{ G}'s \]  

(4)

In Figure 5, it can be observed that the maximum load is presented in the first 50 ms. Likewise, in Figure 6, the maximum displacement is about 420 mm. Therefore, to obtain the ASI, it is necessary to evaluate the speed in the first 50 ms. Figure 7 shows the speed behavior of the armored vehicle.

![Figure 7. Behavior speed of the armored vehicle in the X-axis.](image)

By using equation of uniformly accelerated rectilinear motion, it is possible to obtain the g-forces in the interval of the first 50 ms (see Equation (5)).

\[ a_x = \frac{V_f - V_0}{t} = \frac{3 \times 10^3 \text{ mm/s} - 15.64 \times 10^3 \text{ mm/s}}{0.05 \text{ s}} = \frac{252.8 \text{ m/s}^2}{0.05 \text{ s}} = 25.76 \text{ G}'s \]  

(5)

Finally, the ASI number is obtained, thanks to the values obtained using the ASI equation (see Equation (6)).

\[ \text{ASI}(t) = \left( \frac{\ddot{a}_x}{\ddot{a}_y} \right)^2 = \left( \frac{25.76 \text{ G}'s}{29.58 \text{ G}'s} \right)^2 = 0.87 \]  

(6)

According to the ASI index the armored SUV is within class A, where users can present minor injuries. In this way, the armored vehicle can be considered safe within the parameters of the ASI scale.

2.3. Impact Analysis of the Dummy

A dynamic analysis was carried out, which allowed an assessment of the body damage, emphasizing the HIC and the ASI. We developed this simulation with a virtual model of a
dummy hybrid III male 50th created by Humanetics. This model was designed in 2010, thanks to a collaboration between First Technologies Safety Systems (FTSS), Inc. and Denton ATD, Inc. (Washington, DC, USA). This virtual model offers highly detailed and fully validated finite elements in the LS-DYNA® (Canonsburg, PA, USA), PAM-CRASH® (Bâtiment Le Seville, FRANCE), ABAQUS® (Velizy-Villacoublay, Francia), and RADIOSS® (Troy, MI, USA) codes for typical impact tests; it is the most widely used crash test dummy in the world for the evaluations of automotive safety restraint systems in frontal crash testing [27].

The seat simulation requires a simplified model to be used, which was designed considering two rigid bodies, one that makes up the seat and another as a backrest—the latter with an inclination of 15 degrees from the vertical. This tilt range provides the maximum angle for an appropriate driving position [28]. The dummy position was conducted according to the angles established for good handling for each body extremity. Figure 8 shows the virtual dummy positioned in its driving angle and a real dummy placed in the normal driving position.

![Figure 8. The virtual model of the dummy conditioned for the collision.](image)

Once the dummy is in the right driving position, and the seatbelt is placed correctly, a speed curve is entered to determine the injury degree of the hybrid III male 50th. The present work focuses on the injury suffered by the occupant at the frontal collision in an armored SUV. Thus, to know the injury level for this case, it is necessary to enter the speed curve resulting in the impact analysis of the SUV, with the “particularity” of it being entered in an inverted manner. It is important to note that the curve entered moves the dummy simultaneously as the motor vehicle. Table 5 shows a sequence every 10 ms, starting from 40 ms until the total collision time of 120 ms.

| Time   | Impact Simulation of the Dummy | Time   | Impact Simulation of the Dummy |
|--------|-------------------------------|--------|-------------------------------|
| 0–40 ms | ![Image](image)               | 50 ms  | ![Image](image)               |
| 60 ms   | ![Image](image)               | 70 ms  | ![Image](image)               |

Table 5. Dummy simulation of the frontal collision in the armored vehicle, from 0 to 120 ms.

Figure 9 shows the deceleration of the upper member (head) in the dummy test.
Table 5. Cont.

| Time   | Impact Simulation of the Dummy | Time   | Impact Simulation of the Dummy |
|--------|--------------------------------|--------|--------------------------------|
| 80 ms  | ![Image](image1.png)           | 90 ms  | ![Image](image2.png)           |
| 100 ms | ![Image](image3.png)           | 110 ms | ![Image](image4.png)           |
| 120 ms | ![Image](image5.png)           |        |                                |

The performed analysis leads to the value of the brain injury. In this case, the HIC value was obtained based on the HIC$_{15}$ parameter, which is described as maximum limit 700 [29].

3. Results

Figure 9 shows the deceleration of the upper member (head) in the dummy test.

![Graph](image6.png)

**Figure 9.** Acceleration and HIC$_{15}$ value of the dummy head: (A) Dummy head acceleration behavior; (B) Interval where the highest deceleration is present use to determine HIC parameter.

The red line (A) in Figure 9 represents the head dummy behavior, and the blue line is the HIC$_{15}$ parameter, which has a value of 686.7 over interval $t_1 = 91.84$ and $t_2 = 110.2$. According to the data presented in the previous figure, the result is compared with the HIC value (maximum HIC$_{15}$ level 700) to know the death probability the 50th percentile can suffer. This value determined that the head dummy reached an acceleration of almost 80 G. However, this value is lower than that established as a limit. Therefore, the occupant should remain alive after the collision, but he/she may suffer serious injuries.

It is crucial to obtain the chest deflection in addition to the HIC calculation. Figure 10 shows the maximum deflection captured during the impact.
The following results show the difference between displacements and decelerations on armored and unshielded vehicles. Figure 12 shows acceleration behavior in both vehicles. It can be seen that deceleration peaked at 40 G in the armored vehicle, showing a slight increment compared to 24 G, which allowed us to verify that the response would differ because of the mass change in the vehicle. Moreover, the restitution phenomenon is higher in the armored vehicle at a shorter time-lapse.

Figure 10. Chest deflection of the dummy in the armored vehicle.

In addition, the chest severity index (CSI) can be obtained, as shown in Figure 11.

Figure 11. Chest severity index of the dummy in the armored vehicle.

The following results show the difference between displacements and decelerations on armored and unshielded vehicles. Figure 12 shows acceleration behavior in both vehicles. It can be seen that deceleration peaked at 40 G in the armored vehicle, showing a slight increment compared to 24 G, which allowed us to verify that the response would differ because of the mass change in the vehicle. Moreover, the restitution phenomenon is higher in the armored vehicle at a shorter time-lapse.

Figure 12. Acceleration in a frontal collision of the original SUV vs. the armored SUV.
In Figure 13, one can observe the comparison between the displacement of the frontal part of the SUV model (armored SUV and unshielded SUV) whose values differed by approximately 20 mm, so the ASI value has a variation of less than 0.2 due to the modified SUV having a lower index. Therefore, the armored vehicle would be considered safe for occupants according to the ASI value with the mass increase. This is due to the deformation phenomenon present on the chassis.

Finally, the speed curve on the SUV and used in the dummy is shown in Figure 14. Again, the corresponding speed curves in both cases are shown (armored and unshielded vehicles).

Figure 14 shows the deceleration present in both cases. It is verified that the impact speed decreases as the restitution phenomenon occurs. However, from 0.05 to 0.22 ms, it can be observed that the armored vehicle presents a more static behavior. This factor refers to the vehicle having little energy dissipation during the restitution phenomenon. In this way, the resulting energy is transferred to the passenger, which increases the HIC index.

4. Discussion

Based on the results, we obtained the indices of acceleration severity and head injury criteria. However, to highlight and validate these results, the virtual models used to prepare
this study were validated by the National Highway Traffic Safety Administration (NHTSA). The model used to carry out this study was chosen and manipulated to generate crash tests in a vehicle with an additional mass due to an armored process made to the factory vehicle. It is relevant to note that crash tests made for NCAP measure the passive safety of vehicles, from data obtained from many sensors installed on the dummy and the car. The problem was delimited on dummy protection by the seatbelt to avoid excessive computational resources when performing numerical analyses in this work.

This study informs the reader about the seatbelt performance of the SUV user, with a higher weight that exceeds the original mass of the vehicle. It visualizes a major superior displacement in the vehicle structure and an increase in the G forces in the dummy’s body, supported by the seatbelt. Figure 15 shows the numerical comparison of the armored SUV’s virtual impact and the NCAP’s crash test on an unshielded SUV, where changes in the mass are reflected in the displacement of the vehicle structure.

![Figure 15. Similarity of the crash test in a frontal collision of the original SUV [23] versus the virtual armored model: (a) original SUV; (b) virtual armored model.](image)

Figure 15. Similarity of the crash test in a frontal collision of the original SUV [23] versus the virtual armored model: (a) original SUV; (b) virtual armored model.

This study increases the mass and, consequently, raises the impact energy so that the fastening of the user with the seatbelt concentrated more pressure on the thorax of the human. Figure 16 shows the dummy movement differences in both study cases.

![Figure 16. Dummy kinematic in a frontal collision (A) unshielded SUV speed vs. (B) armored SUV speed.](image)

Figure 16. Dummy kinematic in a frontal collision (A) unshielded SUV speed vs. (B) armored SUV speed.

With the comparative graph of the previous figure, an asymmetric movement is observed in the dummy’s arms in the armored vehicle due to the seatbelt’s retention
system, which supports the thoracic area. This comparison was taken in the maximum load recorded in each study case. In addition, the position of the head has an angle that compromises the neck’s safety. According to Figure 9, the head acceleration in the modified vehicle reaches a maximum of 80 G. In this way, the position of the head is at an angle that compromises neck mobility.

The NHTSA test program shows that the $HIC_{15}$ value obtained in the Ford Explorer 2002 without modifications is around 427.8 [30], while the $HIC_{15}$ from the dummy in the armored vehicle reaches 686.7. This value is near the maximum limit considered acceptable for this criterion. Therefore, this result assumes that the user could suffer significant risks of injuries in a full-frontal collision in the armored vehicle. Considering the HIC score reached by the dummy in both cases, an approximation of injury probability can be made by using the graph “Expanded Prasad-Mertz Curves” [31,32], (Figure 17), where each curve estimates the probability of injury depending on the HIC reached and classified by head injury severity.

![Head Injury Severity](image)

**Figure 17.** Head injury severity “Expanded Prasad-Mertz Curves”.

The graph developed by Prasad and Mertz offers a perspective of the probabilities of head injury using the HIC scores. Table 6 shows a detailed reading of the HIC values in the previous figure.

**Table 6.** Head Injury Severity probabilities.

| HIC Score | 427.8 Unshielded SUV | 686.7 Armored SUV |
|-----------|----------------------|------------------|
| None—injury probability | 37% | 8% |
| Minor—injury probability | 64% | 93% |
| Major—injury probability | 9% | 24% |
| Critical—injury probability | 0% | 0% |
| Fatal—injury probability | 0% | 0% |

Even though the HIC score reached 686.7, this value only increases minor injury probabilities and minor (significant) injury prospects, since using a seatbelt offers enough protection to the passenger. The restraint systems of an armored vehicle offer acceptable
safety levels. It is necessary to underpin it by the ASI value [33]. Hence, the ASI values and their respective injuries are shown in Table 7.

Table 7. ASI index.

| Class | ASI Level | Injuries          |
|-------|-----------|-------------------|
| A     | ≤1.0      | Minor injuries    |
| B     | ≤1.4      | Fractures and short-term memory loss |
| C     | ≤1.9      | Lethal            |

The ASI values were calculated for the two study cases (without armored and armored) from the results obtained in the acceleration and displacement graphs to compare both results later.

\[ ASI(t) = \left[ \left( \frac{\ddot{x}}{a_x} \right)^2 \right]^{\frac{1}{2}} = \left[ \left( \frac{29.33 G'}{34.63 g'} s \right)^2 \right]^{\frac{1}{2}} = 0.84 \]

The ASI equation shows that the Ford Explorer 2002 in the unshielded configuration is in class A. Therefore, this car is considered safe. In the case of armored of the SUV, the result is as follows.

\[ ASI(t) = \left[ \left( \frac{\ddot{x}}{a_x} \right)^2 \right]^{\frac{1}{2}} = \left[ \left( \frac{25.76 G'}{29.58 G'} s \right)^2 \right]^{\frac{1}{2}} = 0.87 \]

According to the severity index obtained from the Ford Explorer 2002 that underwent the armored process, it is within class A, where probabilities of injuries on the occupants are low.

5. Conclusions

In this work, we present a vehicle that was modified due to an armored process. Due to simulations requiring high computational resources, boundary conditions were delimited to avoid overused resources. However, the most significant deficiency in this study was not contemplating the passenger compartment and the airbag. These factors could evaluate a user’s probability of survival (or death) with more accuracy. The results obtained from this work show low-cost and straightforward ways to measure new crash test cases.

It is important to note that the results obtained from this work show similar deceleration curves as those in the George Washington University studies. The car’s structure was able to dissipate all energy generated by the car body’s displacement, and it was observed that this displacement was just slightly higher in the armored vehicle. It should be mentioned that the addition of steel plates at the vehicle doors would improve the structure stiffness. However, the level III armored does not focus on altering the vehicle’s structure, so the structural stiffness is not changed, and it can continue to absorb energy during the impact. The structural stiffness can limit this energy absorption in a higher armored where the structure is affected. Although the car body dissipates the highest energy, the deceleration of the dummy is not as fast as the dummy in the unshielded vehicle, due to the increased mass and the increased amount of kinematic energy the vehicles dissipate at the same time intervals. Therefore, the HIC number calculated in the armored vehicle analysis is “raised”, having a value close to the maximum allowed limit, increasing injuries.

On the other hand, the maximum value of the CSI is 326, which is a number considered acceptable with a chest compression of 28 mm. This value describes a low probability of suffering from an injury. However, considering that new regulations in the automotive industry force car companies to build their cars with airbags as standard equipment, it is very likely that the chances of sustaining severe injuries can be dismissed.
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