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GUIDO MUZIO CANDIDO
PAULO CARLOS KAMINSKI

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The addition of Design for Armoring as an engineering methodology in the development of premium civilian vehicles

Guido Muzio Candido, Paulo Carlos Kaminski
Polytechnic School of University of Sao Paulo

Abstract

Brazil for more than two decades is the largest producer of civilian armored vehicles in the world, where in 2018 almost 12,000 new vehicles received this type of protection in the country, contributing to an estimated armored fleet reaching almost 220 thousand units. In 2019, there was an estimated growth of between 20% and 25% compared to the previous year, where premium segment vehicles characterize the majority of civilian armored vehicles. In this context, this paper presents an overview, in the country, of the main models of civilian vehicles that are armored at ballistic protection type III-A level against handguns, according to the NIJ 0108.01 standard, from the National Institute of Justice of the United States. In this sense, just as automakers adopt DFM and DFA, Design for Manufacturing and Design for Assembly, as part of their vehicle developments, the purpose of this paper is to present and propose the addition of DFAr, Design for Armoring in premium vehicle projects. The main idea is to properly design the vehicle by considering the inclusion of opaque and transparent protective materials in the vehicle system still during the assembly process as to guarantee automotive and ballistic quality in case they are armored according to NIJ III-A protection level. The objective is to provide, still during the design phase, the necessary spaces in the automobile for the correct installation of these armoring materials, to safeguard the original functionalities of the automotive components and simultaneously provide the required ballistic protection of the vehicle while attaining all quality requirements.

Introduction

In Brazil, where the armored civilian vehicles have an estimated fleet of almost 220,000 vehicles in 2018, mostly armored according to the NIJ 0108.01 type IIIA protection level, being considered the largest market in the world according to ABRABLIN data, the Brazilian Armoring Association. The fleet of Brazilian civilian armored vehicles is five times larger than the second country in the ranking, Mexico, which has approximately 50,000 armored vehicles in circulation. Also according to ABRABLIN, approximately 12,000 new vehicles were armored in Brazil in 2018, with an estimated growth of 20% to 25% in the sector's production, with an estimation of 15,000 units produced in 2019 [1].

Customers, in general, associate the idea of armoring premium vehicles as increasing its safety and comfort. Based on ABRABLIN survey, in 2018 the Jeep Compass was the vehicle most armored in Brazil. Toyota's Corolla was the second, followed by the Volvo XC-60, Land Rover Discovery and BMW X1. In general, it is observed that in Brazil, the civil vehicle armoring market is mostly composed of *premium* brands and models [1].

NIJ 0108.01 standard, from the National Institute of Justice of the United States, specifies requirements to ballistic resistant materials (armor) intended to provide protection against gunfire considering levels of ballistic performances, from I to IV. For any performance level, NIJ's test protocols requires that the bullet does not perforate the testing specimen. The ballistic resistant materials for armoring purposes include metals, ceramics, transparent glazing, fabric, and fabric-reinforced plastics. For armoring vehicles, there are combinations that consider vehicle´s structure as a system protection. In Brazil, the NIJ 0108.01 standard, is the reference for armoring civil passenger vehicles, from ballistic protection level I to level III-A, and level IV for specific automobiles, such as cash transport vehicles. The NIJ 0108.01 type IIIA protection level materials are designed to stop 9 mm FMJ (Full Metal Jacketed) bullets and .44 Magnum Lead SWC (Semi Wadcutter) Gas Checked bullets, both at a velocity of 426 ± 15 m/s (or 1400 ± 50 ft/s) [2].

Civil armored passenger vehicles in Brazil are usually assembled in automotive armoring service provider (AASP) plants, where almost all of them, with few exceptions, do not follow the minimum requirements as stablished by the Original Equipment Manufacturers (OEM) standards. To summarize, brand new armored automobiles usually only keep the original warranties in the engine and mechanical systems or components where the armoring process is not applied. Therefore, other original components, where armoring parts are installed are excluded from the OEM coverage such as: airbags, power window regulators, front and rear door assemblies, roof panels, sunroofs, door hinges, seats, tailgate assemblies, upholsteries, suspensions, electrical and electronic systems, all of them located inside the passenger compartment within the car body [3].

Basic Design Methodologies Overview

The increasing of global economy, new technologies and a variety of technical standards and new models, influenced decisively in the continuous improvements occurred in the automobile industry. Similarly, basic design methodologies are constantly being proposed to meet the product, process, quality and safety challenges of consumer market and demands, OEMs production plants and government regulations. Motivated by industries interest in profit gains, cost reductions, and pressure to achieve sustainability, the relevant design basic concepts, such as Design for Manufacture (DFM), Design for Assembly (DFA), Design for Disassembly (DFD), among others, have been introduced in automotive companies as an important tools for product design. An overview of these design concepts is presented in Table 1 [4].

Table 1. Main basic design concepts in product design and development [4].

Design Conception	Description
Design for Manufacture (DFM)	Design to improve manufacturability of products.
Design for Assembly (DFA)	Design of products so that they are easy to assembly.
Design for Manufacture and Assembly (DFMA®)	Design of products to address both DFM and DFA.
Design for Disassembly (DFD)	Design to facilitate disassembling of products.
Design for Service (DFS)	Design to reduce maintenance cost of products using previous service information.

Design for Manufacture and Assembly (DFMA®)

The Design for Assembly (DFA) analysis is conducted first, leading to a simplification of the product structure. Then, early cost estimates for the parts are obtained for both the original design and the new design in order to make tradeoff decisions. During this process, the best materials and processes to be used for the various parts are considered. Once the materials and processes have been finally selected, a deeper analysis for Design for Manufacturing (DFM) can be carried out for the detail design of the parts [5].

DFM and DFA are the integration of product design and process planning into one common activity. The goal is to design a product that is easily and economically manufacturable. So, DFM is a systematic procedure to maximize the use of manufacturing processes in the design of components and DFA is a systematic procedure to maximize the use of components in the design of product [6].

Design for manufacture and assembly (DFMA®) combines the principles of DFA and DFM. While Design for Manufacturing attempts to reduce the cost of individual parts by minimizing the complexity of the parts, Design for Assembly attempts to reduce the cost of the overall assembly through minimizing the number of operations and simplifying the assembly process [7]. Thus, DFMA® methodology can reduce the manufacturing costs through reducing overall parts of the product and redesign of the parts, so the product will be easy to manufacture and assemble. In particular, DFMA® is a method for evaluating the manufacturability of product design and assembly design. It is a tool to identify unnecessary parts in assembly, and to determine the time of manufacture and assembly costs [8].

The DFM benefits are: simplify fabrication and assembly; improve ergonomics; reduce rework; reduce mass; improve serviceability; increase process quality; reduce logistic time; reduce time to market launching; reduce production problems; reduce program budget [9].

Figure 1 summarizes the steps taken when using DFMA® during design. The DFA analysis is first conducted leading to a simplification of the product structure. Then, while using DFM, early cost estimates for the parts are obtained for both the original design and the new design in order to make trade-off decisions. During this process the best materials and processes to be used for the various parts are considered [10].

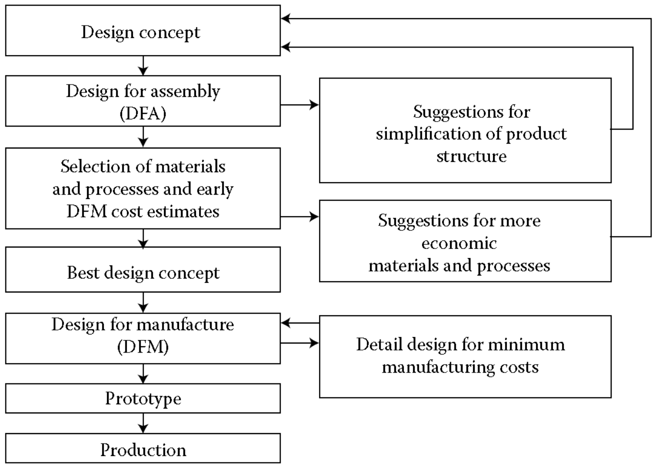

Figure 1. Typical steps taken in a DFMA® study [10].

DFMA® Principles

The main principles of DFMA® that could be applied to a variety of products, including automotive components and systems, are listed below, in no particular order [5]:

1. minimize part count: limit the number of parts to decrease assembly steps;
2. minimize fastener variety: eliminate or reduce the number of fasteners in an assembly;
3. assemble in the open: allow adequate access and visibility of the assembly area at all times;
4. encourage modular design: make the design modular instead of inter-dependent;
5. don't fight gravity: ideally place items down onto assembly, and not from the side or bottom;
6. design self-aligning parts: make parts that self-align with mating parts;
7. multi-use parts: use "paired" or symmetrical parts instead of right/left or top/bottom parts;
8. minimize assembly surfaces: eliminate the need to reorient parts or tools for assembly;
9. design to process capability: ensure that parts can be made using the existing machine and supplier capabilities.

Design for Disassembly (DFD)

Starting in the '90s, increasing research on disassembly has been conducted to establish efficient disassembly sequence planning, which is also applicable in Design for Disassembly (DFD), maintenance or repair because these operations always require at least partial disassembly of the products to retrieve or repair certain parts. The main goal of remanufacturing is to restore the performance of a used product and bring it back to the market through a series of activities, such as core retrieval, disassembly, sorting, inspection, cleaning, reconditioning and reassembly. The functionality of the remanufactured products should at least match or even exceed the specifications set by the OEM, by using latest technologies [4].

Products may be disassembled to enable maintenance, enhance serviceability and/or to affect end-of-life (EOL) objectives such as product reuse, remanufacture and recycling. Then, the design for disassembly is necessary condition for products to be economically recycled, by improving components and material reuse and remanufacture processes, extending the service life of the products and components. The maintenance can be simpler and the output of all these improvements requiring less raw material and energy waste and better performance in terms of life cycle evaluation. Benefits from using DFD are [9]:

1. core business components can be recovered;
2. metals separation without contamination, improving process quality;
3. dismountable non-metallic parts can be re-processed.

Products that are designed for disassembly and remanufacturing can deliver much greater savings than would be achieved through remanufacturing of a product that is not designed with this intention. Therefore, in the context of design for disassembly (DFD) for remanufacturing, the fundamental requirements are [11]:

1. simplify joining method for quick disassembly;
2. prioritize retrieval of cores over non-remanufacturable parts;
3. protect of product core to maintain part's integrity;
4. incorporate DFD as early as possible in the product design stage in order to facilitate disassembly processes.

Design for Service (DFS)

Serviceability that affects lifetime servicing costs is another important consideration that leads to another design concept known as Design for Service (DFS). DFS utilizes previous maintenance and service information to optimize the design of new products for greater reliability and lower maintenance cost in the future [4].

Regarding products, e.g. systems, assemblies and parts, DFS is useful for designing components that are easy to disassemble for servicing purposes. This could be accomplished by observing the following main directions, not necessarily in this sequence:

1. review labor costs for product disassembly;
2. reduce the number of assembly operations;
3. ensure that the product service life is appropriate for its purpose;
4. design modular products to be disassembled for service by using a quick-change replacement modules;
5. reduce the number of parts used in an assembly;
6. design sub-assemblies to keep the function of the component;
7. reduce fragile parts to enable re-assembly.
8. prepare to use a friendly and simple assembly, disassembly and maintenance services;
9. use standard and interchangeable types of fasteners;
10. design maintenance parts of a size to be handled by one person;
11. design for multiple detachments with one operation;
12. add error proofs (*Poka-Yoke*) during disassembly, reassembly;
13. allow easy access for tools and adjustment manipulations.

Design Methodologies in Automotive Sector

The product development processes (PDP) in automotive industry is organized in stages or gates, which consists in: market study; product development; product planning; style concepts; program classification; strategic planning; style development; product and process development; tests and validations of the product and the process; automobiles from pilot production; start of the automobile's production and Launch the product in the market [12]. OEM suppliers in this context are usually involved at an early stage of automotive PDP as a co-designer or as an integrated engineering team work. Literature reviews confirm that the participation of the suppliers in the PDP may significantly contribute to improve the performance of the process in terms of time, quality and cost [13]. These integrations allow faster technological innovations and allow the company specializing in its core business, i.e., design and assembly of the vehicle, and not its specific parts.

So, the usage of the basic design methodologies for OEM, supplier product and manufacturing engineering teams at PDP, as the tools for a new vehicle design, are briefly shown in Figure 2.

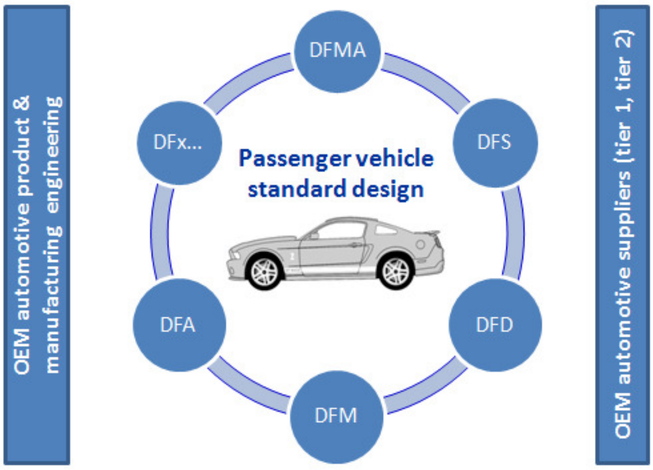

Figure 2. Schematic approach of OEM and its suppliers applying DFx methodologies in a passenger vehicle design.

Civil Armored Passenger Vehicle

In a typical civil armored vehicle with NIJ IIIA protection level standard, the entire passenger compartment is enclosed in lightweight composite armors, such as aramid plates, and stainless steels that are impervious to handgun and submachine gun munitions. Also the car window set is replaced by the transparent armor set, which are composed of layers of glasses and polymers.

The usually locations of protection materials in passenger compartment vehicles are schematic shown on Figure 3. In general, stainless steel parts are fastened on A, B, C (and D for SUVs) pillars, door locks, roof rails, and other small or rounded areas. Aramid plates are normally assembled on uniform and flat areas, such as roof, tailgate inner panel (SUVs), under the hood (near the windshield) and at the front and rear door panels. Finally, armored glass set is assembled with an appropriate overlap of parts to protect the passenger compartment [3].

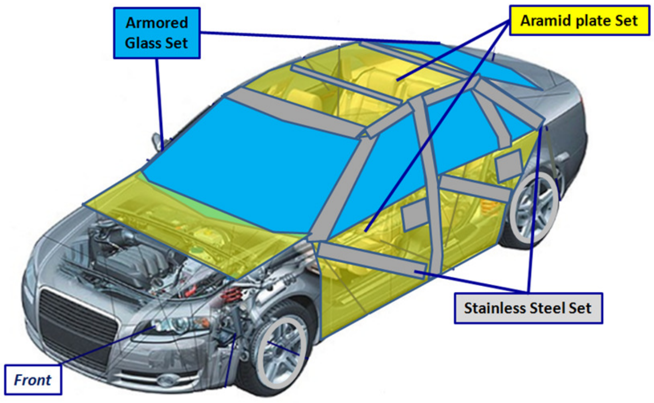

Figure 3. Typical civil armored vehicle with protective material locations [3].

Civil Passenger Vehicle Armoring Process

Two types of armors are used in the armoring process, transparent and opaque. Transparent armor is used for the windows and consists of dense layered ballistic glass that is laminated to a tough inner spall shield of resilient polycarbonate. Opaque armor consists of lightweight composite armor (aramid plate) and high-hardened ballistic stainless steel. Once the vehicle has been armored, it's reassembled to mirror the original factory finish.

A typical civil passenger vehicle armoring process is summarized on Table 2. This paper focuses on the design analysis of items 4, 6, 7, 8, 9, 10 and 11, related to the disassembly and reassembly of OEM passenger compartment parts and the assembly of ballistic parts.

Table 2. Typical civil passenger vehicle armoring process [3].

	Armoring vehicle process	Explanations
1	Customer order	Management vehicle control
2	Service order	Management process control
3	Check in inspections	OEM warranty; quality control
4	OEM parts disassembly	Quality process
5	OEM parts identifications	Quality control; traceability
6	Vehicle preparation	Ass. protection (risks, scratches)
7	Stainless steel assembly	Ballistic part assembly sequence
8	Aramid plate assembly	Ballistic part assembly sequence
9	Armored glass assembly	Ballistic part assembly sequence
10	OEM parts reassembly	Final vehicle assembly
11	Vehicle tests	Static & dynamic vehicle analysis
12	Check out inspections	Final quality audit
13	Customer vehicle delivery	Customer warranty documents

Design for Armoring Methodology Proposal

Premises

Usually premium passenger vehicles sold in Brazil, before they were armored, they have been originally developed, validated and produced in Europe, USA or Japan plants. As in these markets, the customers do not request for this demand, manufacturers do not consider developing armoring designs in their premium vehicles, even those that are also exported to other countries of origin, for example, to Brazil or to Mexico markets. In this scenario, the local AASP companies carry out to the armoring procedures of imported vehicles starting by disassembly and reassembly the original parts, and with few exceptions, they do not consider the automotive product and process engineering criteria and recommendations from OEMs, especially regarding to safety features, such as airbags, for instance.

In addition, in Brazilian market, brand new civilian imported automobiles are armored after being sold to customers at dealerships in most cases without OEMs knowledge or without OEM warranty certifications. The quality and the guarantees of new protected vehicles related to the original equipment, such as active and passive safety features, corrosion and body structure, brake systems, front and rear suspensions, and other original coverage of the vehicles, for example, are automatically lost. Customers are often not aware of the loss of the OEM warranties after their vehicles have been protected. In Brazil, with few cases, there is no automotive armoring qualification process approval issued by OEMs to the AASPs, which certify the armoring processes, such as an OEM Tier 1 or Tier 2 supplier's product and process approvals [3].

According to author's background and work experience, those evidences previously described have been obtained from armored vehicles customer complain reports, AASP shop floor disassembly procedure reviews and additional costs of reworks and repair service orders, maintenance and service bulletins applications and, also information obtained from dealership technical reports.

DFAr Proposal in Automotive Design Phase

During early phases of PDP for a premium vehicle that is defined to be armored afterwards its original assembly, the product and process engineering teams would include in the passenger compartment, a package system for the additional NIJ IIIA ballistic level components. This package system would then be analyzed by OEM engineers together with AASP engineers, as a part of the design team. Based on basic DFx methodologies previously introduced, this paper proposes the addition of DFAr, Design for Armoring, with the current DFMA®, DFD and DFS analysis to be applied for an armoring vehicle design by OEMs, automotive suppliers and AASPs, as an integrated team work. The product 'freezing' gate phase of the armored vehicle design program in a product development process would be concluded after DFAr reviews and validation with the team during the product and process program phase to assure that the product design with armoring features included in the project is feasible, mature and comply with OEM product/process and AASP production requirements.

With this integrated team, the DFAr methodology consist on the ballistic part designs to fit the vehicle package analysis in order to guarantee enough and adequate spaces for the addition and correct assembly of armoring components in the car body, also considering the reassembly of vehicle parts in a right sequence without causing any damages or interferences that may result in malfunctions or interferences on the original systems previously installed nearby the protected parts inside the vehicle. The objective of DFAr is also to safeguard the original functionalities of the automotive components and simultaneously provide the required ballistic protection of the vehicle while maintaining the quality guarantee.

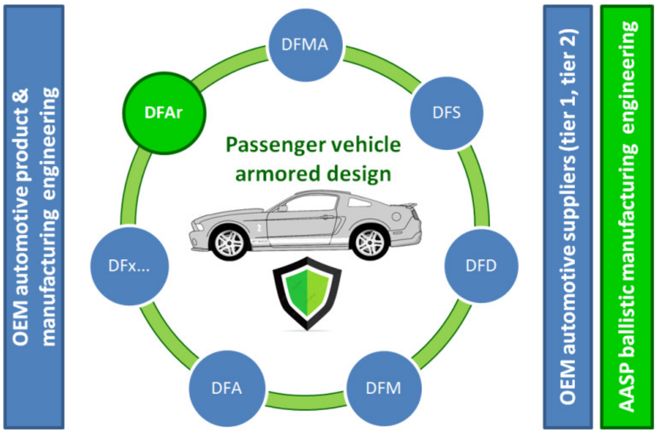

Figure 4. Schematic approach of OEM, suppliers and AASP applying DFx and DFAr methodologies for the design of a passenger vehicle that will go through armoring afterwards.

The objectives of DFAr application in the design phase consist of:

1. minimize the changes of OEM vehicle performance data, such as fuel consumptions, power-to-weight ratio, center of gravity, brake systems, among others;
2. keep the OEM customer warranties together with ballistic protection certification;
3. avoid the increasing of redesign time for future AASP shop floor needs;
4. avoid the risk of failure of OEM vehicle systems after armoring process, such as curtain airbags, electronic modules, electrical systems, among others;
5. keep the warranty of body metal frame structure against corrosions;
6. reduces labor costs of armoring shop floor process, such as reworks, part remanufacturing processes;
7. standardize the armoring process and vehicle validations with OEM quality requirements.

DFAr specificities

DFAr has specificities according to each of the armoring material that will be used, such as aramid, stainless steel and glasses, in order to guarantee the integrity and functionality of the respective material when installed on the vehicle. The topics of bulletproof protection material in NIJ IIIA ballistic protection level are described as follow.

Usually aramid plates for NIJ IIIA ballistic protection level has eight or nine layers (standalone) and it needs to be completely sealed against water intrusion when installed at vehicle wet areas, such as, front doors, rear doors and tailgates (SUV, sport utility vehicle versions) in order to avoid the loose of its ballistic performance due to a hygroscope properties. Also, the ballistic performance of aramid plate is better when installed (glued) at flat areas, such as roof and quarter panels (SUV). For serviceability, gluing process criteria shall be considered.

The main process of stainless-steel assembly is through fastening by using screws on the vehicle, usually localized in inner pillars and nonplanar surfaces, always respecting the restraint and curtain airbag envelope areas and the wiring harness routes. Also, the ballistic performance of stainless steel is necessary when installed at small or thin areas, such as A, B, C and D pillars. For restraint and safety systems serviceability, the usage of standard fasteners with controlled torque is considered.

Glass window sets, which replaced OEM sets, have more thickness than the original sets and they are composed by a sort of laminated glass and polyurethane layers. Fixed glasses, such as windshields and rear glasses are glued in the vehicle structure normally with an additional stainless steel frames all around for ballistic overlapping with the opaque protection parts. Door glasses are assembled with additional supports to comply with power window lifter mechanism efforts and operations in order to keep the OEM design and functionality. For serviceability, the usage of standard fasteners with appropriate torque control shall be considered.

During the DFAr analysis together with current methodologies on automotive engineering, the armoring design phase for a bulletproof protection vehicle, is guided by the following principles, ideally in this order, are described to be performed simultaneously with product and process engineering, considering the specificities, restrictions and conditions of each vehicle, to assembly opaque and transparent armor materials:

1. define OEM specification targets for civil armored vehicles, such as maximum armoring payload (ground vehicle weight, GVW), luggage capacity and fuel consumptions;
2. define ballistic specification targets for civil armored vehicles, such as the protection level and the shooting vehicle map;
3. check passenger compartment 3D interface packaging analysis by keeping OEM design, functionality and tolerance requirements and defining ballistic protection areas;
4. prioritize the interchangeability of components, fasteners and tools applied for both OEM versions (with or without armoring);
5. define specific automotive statement of requirements, ASOR, from OEM with product and quality requirements, standards, tests and automotive validations;
6. define specific ballistic statement of requirements, BSOAR with ballistic requirements, standards, tests and validations;
7. create standard work instructions for disassembly and reassembly OEM parts with appropriate tools and safety procedures, keeping OEM quality assembly processes;
8. create standard work instructions for assembly ballistic parts with appropriate tools and safety procedures, with quality assembly processes;
9. create serviceability and maintenance work instruction manuals for OEM parts with appropriate tools and safety procedures;
10. create serviceability and maintenance work instructions manuals for ballistic parts with appropriate tools and safety procedures.

DFAr Application Examples

Prototypes are used from the initial phase of the PDP, where technical and marketing teams work to meet the specifications of a new product, in addition to understanding users' needs, going from the manufacture to product introduction into the market . The use of CAD (computer-aided design) and CAE (computer-aided engineering) systems are important tools to create and validate the virtual prototypes (VP) in an automotive PDP [14].

During the DFAr analysis, there are situations in which the design of some OEM parts have to be adaptaded or changed to fit the assembly of the protection components. An example of DFAr analysis using VP is shown on Figure 5, before and after armoring analysis of the same vehicle area. In the "A" pillar of the vehicle, the trim pillar has an attachment bracket redesigned to allow the additional stainless steel assembly for an armored version. The DFAr analysis consider the "A" pillar garnish trim feasibility tooling study in order to be able to produce both versions of the same vehicle, standard and armored.

The benefits of using DFAr for the automotive approach are: reduce manufacturing process by following the standard assembly process instruction sheets; keep the original funcionality, the original position and the serviceability of the curtain airbags; keep using OEM standard fasterners. The benefits of using DFAr for the ballistic approach are: guarantee the protection area required for the stainless steel; avoid interferences between OEM parts.

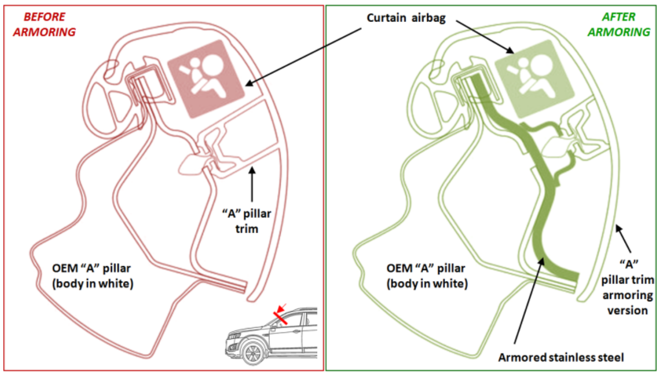

Figure 5. DFAr interface analysis with curtain airbag in the "A" pillar cross section view, before and after armoring process.

Another example of DFAr by using CAD and CAE to design armoring parts and redesign OEM parts involved, is shown on two sections on Figure 6, before and after armoring analysis of a potential vehicle to be armored. In the front door lock section of the vehicle to comply with ASOR and BSOR simultaneously, the upper door panel trim and inner door upper frame have to be redesigned to match with additional armored glass, thicker than the OEM, stainless steel and aramid panel assembly. In this cross section, the DFAr analysis considers the following engineering analysis: comply with OEM gaps and flushes tolerances for door window up and down packaging movements, keep door lock system serviceability (stainless steels screwed) and a door trim panel tool to allow the production of both versions, standard and armored.

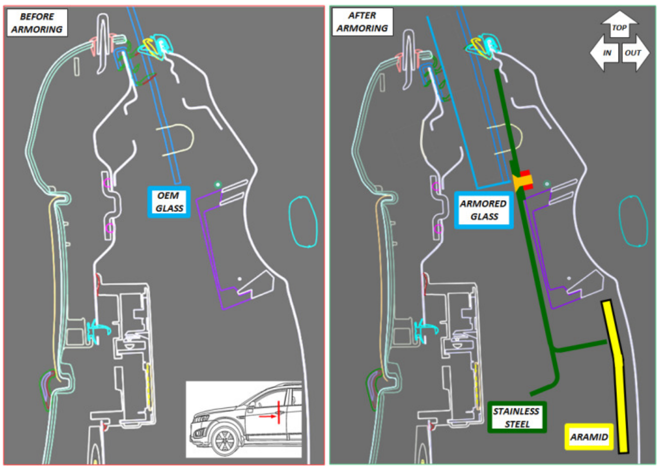

Figure 6. DFAr interface analysis with armoring components in front door lock section view area, before and after armoring process.

Summary/Conclusions

Based on DFMA®, DFM and DFS principles, the proposal of DFAr methodology is to be a guideline for civil vehicles armoring product and process design in NIJ IIIA ballistic level. The objective is to guarantee, since de early phases of the PDP, the feasibility of disassembly and reassembly of automotive components and, simultaneously, the correct assembly of bulletproof materials on a civil armored vehicle. Main benefits of such approach are to comply with the automotive and the ballistic protection requirements and keep the OEM warranties, design quality and functionalities of the respective armored vehicle structure. DFAr would include, also, the AASP engineers in the design team, supporting the OEM and supplier engineers. In addition, DFAr focus on keeping the original automotive passive and active safety system features and its product/process requirements would guarantee the right bulletproof assembly of parts in the vehicle compartment. The DFAr could be useful reference for OEMs established in Brazil to redesign, to adjust and to validate NIJ IIIA level ballistic specifications on potential civil armoring vehicles by developing together with AASP companies all manufacturing processes necessary to minimize labor costs, material costs and unnecessary reworks and, mainly, keep the OEM automotive warranties and requirements.

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Contact Information

Guido Muzio Candido is a Ph. D. student in Mechanical Engineering and he is current Automotive R&D Engineer Collaborator at CEA, *Centro de Engenharia Automotiva* (Automotive Engineering Center) from *Escola Politécnica da Universidade de São Paulo* – EPUSP. He is also Automotive Product, Quality and Armoring Engineering Consultant. He graduated as Master in Automotive Engineering from EPUSP (2005), Post graduated in Automotive Engineering from FEI University, (1998) and graduated in Mechanical Engineering from Mauá University (1997). In Brazil, he used to work as Product Engineer Coordinator at EDAG, Quality Engineering and Advanced Engineering at PSA Group and New Product Development Engineer at General Motors and at Ford Motor Company. E-mail: guido.candido@usp.br

Dr. Paulo Kaminski holds a degree in Naval Engineering (1986). He has a master's degree and a Ph.D. in Mechanical Engineering (1992) from *Escola Politécnica da Universidade de São Paulo* - EPUSP. He is also graduated in Business Administration (1990), and was a post-doctoral researcher at the Technical University of Darmstadt with fellowship from the Alexander von Humbolt foundation (1993-1994). Since 2009, he is a Full Professor of the Mechanical Engineering Department from EPUSP. He is the current head of Automotive Engineering Center (AEC), Coordinator of Automation and Technology Project Center, Coordinator of Automotive Engineering specialization course at EPUSP and he is an International collaborator of CIRST (*Centre Interuniversitaire de Recherche sur la Science et la Technologie de* Quebec, Canada). E-mail: pckamins@usp.br

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Definitions/Abbreviations

AASP Automotive armoring service provider

ABRABLIN *Associação Brasileira de Blindagem*, Brazilian Armoring Association

ASOR Automotive statement of requirements

BSOR Ballistic statement of requirements

CAD Computer-aided design

CAE Computer-aided engineering

DFA Design for Assembly

DFAr Design for Armoring

DFM Design for Manufacture

DFMA® Design for Manufacture and Assembly

DFS Design for Service

FMJ Full Metal Jacketed

GVW Ground Vehicle Weight

NIJ National Institute of Justice

OEM Original Equipment Manufacturer

PDP Product development process

SUV Sport utility vehicle

SWC Semi Wadcutter

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