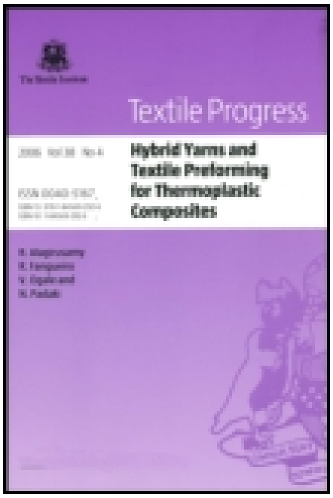

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Airbags

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In recent years, safety systems such as seat belts and airbags have been one of the fast-growing sectors within the automotive industry. Seat belts and airbags have made driving substantially safer since their introduction. Airbags are safety systems used to cushion the driver or passenger during a collision and reduce bodily injuries. The technology involved in the manufacturing and working of airbags is complex. Since the early stages of development, airbag technology has been undergoing continual evolution in terms of design, materials and performance. Airbags are typically made from woven fabric, which may be coated or uncoated but must be impermeable to gases and flame resistant. In terms of their operation, modern airbags are smart restraint systems, which can tailor the deployment of the airbag according to the crash severity, body size of the occupant and proximity of the occupant to the airbag system prior to deployment. The future of airbags is extremely promising because there are many diverse applications ranging from motorcycle helmets to aircraft seating. In this article, an outline is given of the historical development of airbags and their value in saving lives is illustrated by supporting statistical data. The essential parameters required for airbag yarn and fabric components are discussed in detail. In addition, the processes involved in the manufacture, assembly and testing of airbag systems are explained. The mechanisms and chemical reactions involved in the deployment of different types of airbags are also discussed, and recent developments in airbag design and their possible future applications are reported.

Keywords: airbag; seat belt; automotive textiles; safety; restraint system

1. Introduction

The market for automotive textiles is one of the most important in the technical textiles sector. Approximately 42 square metres or about 20 kg of textile materials is used as interior trims (such as seating areas, headliners, side panels, carpets, reinforcements, linings, underlay fabrics, tyres, hoses and airbags) in each of the 45 million or so cars sold every year globally [1]. Figure 1 shows the distribution of fabrics used in the different parts of a car [2]. Airbags constitute about 3.7% of the textiles used in a car. In the last two decades, the use of airbags in cars has gained significant importance due to their active role in preventing injuries and saving lives in minor to severe crashes [3,4].

An airbag is an automotive safety restraint system built into the steering wheel and various other strategic locations of a vehicle [5]. Airbags were developed as a concept for

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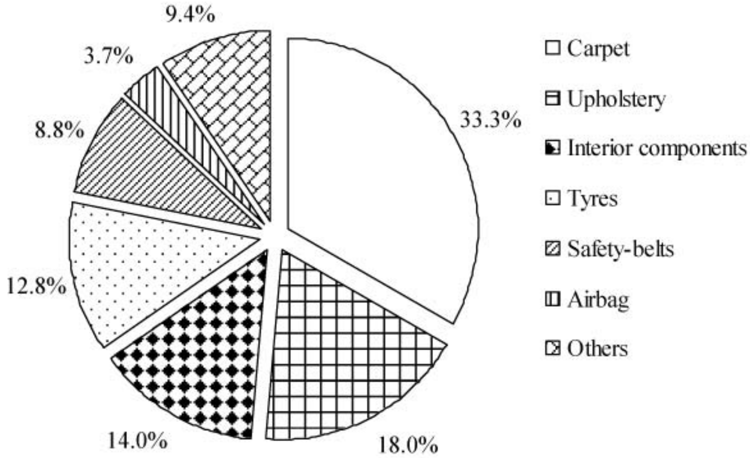


Figure 1. Typical breakdown of amounts of textiles used in a car [2].

a system that would restrain automobile drivers and passengers in an accident. Steering-wheel-mounted airbags help to protect the head and upper body of the driver from injury during a collision. The rise in standard of living and safety consciousness in developed nations like Australia, Europe and the USA led to increasing demand for automobile manufacturers to introduce safety devices like seat belts and airbags, and made airbags a ubiquitous supplementary measure in modern cars aimed at improving the safety of automobile occupants.

In an automobile, in addition to comfort, aesthetics, speed, mileage, durability and efficiency, safety is a priority for the driver and passengers. Airbags work as a supplementary safety device for an occupant who is correctly restrained with a seat belt. In the event of a collision, seat belts hold the occupant securely in place and the airbags inflate instantly to cushion the passenger with a gas-filled pillow. The airbag is a part of an inflatable restraint system known as an air cushion restraint system (ACRS) or airbag supplemental restraint system. Modern vehicles incorporate a wide variety of airbags in the form of driver, front passenger, side-impact and rollover airbags in various side and frontal locations.

Different terminologies have been used over time for airbags. The first airbag introduced by General Motors (GM) in the 1970s was marketed as the ACRS. In North America, airbags are known as a supplemental restraint system (SRS) and supplemental inflatable restraint. It is reflected in these terms that the airbags work as a passive supplement to other active restraints such as seat belts. Airbags are termed passive devices, as no action by the vehicle occupant is required to activate or use them. On the other hand, seat belts are considered active devices, as the vehicle occupant must act to enable them.

From the beginning, in common with other products aimed at the consumer market, the aims in airbag design have been to improve their performance and reduce their cost through continual evolution, resulting in a variety of airbag substrates with reduced package size and improved performance becoming commercially available at lower cost. The important factor is the cost–performance ratio, rather than cost alone.

Both coated and uncoated airbags today are significantly improved over earlier designs, as they are lighter in weight, have improved performance, show better ageing characteristics and have better packability. However, the market share of coated airbags is in decline due to their cost and the environmental issues associated with the coating process whereas cost reductions in uncoated fabrics have been able to be realised by reducing both the material content and cost of manufacture. Moreover, problems such as poor seam strength, bulkiness, gas leakage and variations in permeability originally associated with some uncoated fabrics have been overcome by improved fabric and seam engineering. Even so, as yet, no single type of airbag material may be practical for all applications due to the need for design flexibility imposed by associated factors such as steering-wheel design (pan size), inflator type (azide, gas-assist or liquid), inflator aggressiveness and bag type (driver, passenger, side, knee-bolster or others) [6], hence the existence of a variety of airbag designs amongst different automobile manufacturers.

1.1. Importance of airbags

Seat belts and airbags are primarily designed to restrain the vehicle occupants during a crash. Seat belts are the primary method of occupant restraint for all impact speeds; airbags are a supplement to the seat belts which have proven to be very effective in reducing the severity of injuries. Airbags are passive restraint devices that provide the greatest safety benefit when used in conjunction with properly-fitted and adjusted seat belts; by contrast to the seat belts, however, they are ineffective at low-impact speeds as there is insufficient force generated to trigger the airbags.

1.1.1. Statistical data on lives saved

The use of airbags and seat belts helps in reducing severe injuries and deaths, although they themselves can cause certain injuries during an impact. From analysis of data collected by the US Fatal Accident Reporting System between 1992 and 1997 from head-on collisions between matched cars, it was found that combined airbag and seat belt use reduced driver mortality by more than 80%; the odds of dying in a head-on collision were reduced by approximately two-thirds when the driver was in a car whose airbag deployed compared with one whose airbag did not deploy or was not equipped with an airbag [7].

However, for certain types of thoracic injury, it is the seat belt which provides the protection regardless of airbag deployment [8]. Having begun its evaluation of its Federal Motor Vehicle Safety Standards (FMVSS) in 1975, by October 2004, the US National Highway Traffic Safety Administration (NHTSA) had evaluated the effectiveness of virtually all the life-saving technologies introduced into passenger cars, pickup trucks, sports utility vehicles and vans in the USA from 1960 to the early part of the twenty-first century. Vehicle safety technologies saved an estimated 328,551 lives from 1960 through 2002. The annual number of lives saved grew quite steadily from 115 in 1960, when a small number of people used lap seat belts, to 24,561 in 2002, when most cars and light trucks were equipped with numerous modern safety technologies and safety belt use on the road had risen to 75%. In 2002, according to the NHSTA evaluation, airbags were the third most effective safety technological measure after seat belts and energy-absorbing steering assemblies [9]. A survey by Glassbrenner [10] completed in 2003 (Figure 2) showed that between 1991 and 2001 in the USA, about 109,000 lives were saved by seat belts and 8000 by airbags.

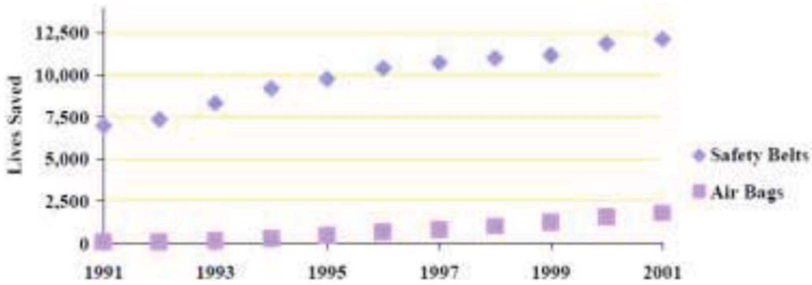


Figure 2. Lives saved by safety belts and airbags [10].

1.1.2. Growth in the market for airbags

A report in 1996 showed that more than 15 million vehicles were equipped with driver and passenger airbag safety systems by that time [11], and between 1993 and 2001, the global vehicle occupant restraint market grew at an average rate of 12% annually [12], and according to the 2012 GIA (Global Industry Analysts) report on automotive airbags, the world airbag market is projected to reach 474 million units by the year 2017 with side-impact airbags representing the fastest growing market segment [13]. The growth of airbags will be primarily driven by an increase in the production of passenger cars, increasing federal regulations, growing awareness of safety, development of smart sensors and new airbag designs (such as curtain airbags, side-impact airbags).

1.2. History of airbags

The concept of airbags dates back to the 1940s, when they were first manufactured and investigated by automobile engineers [14]. The majority of automotive patents were issued in the 1960s but the leaders were Linderer, who designed an airbag and was awarded a German patent (Patent DE 896,312 filed 6 October 1951; issued 12 November, 1953), and Hetrick, who filed later but was issued with a US patent slightly earlier (US Patent 2,649,311, filed August 5 1952; issued 18 August, 1953) [15]. The airbag designed by Linderer was based on a compressed air system, released either by bumper contact or by the driver (later, it was found that compressed air could not inflate Linderer's design of airbag fast enough for maximum safety, making it unadoptable). Hetrick's airbag design was also based on compressed air, his idea being to provide protection for his family in his vehicle during accidents. Although Hetrick worked with some leading American automobile manufacturers at that time, his idea was not successful either, in his case due to the unwillingness of the automobile manufacturers to invest in his field of research. The first commercially applicable airbag design, and the forerunner of the most current systems, is credited to the designs of Yasusaburo Kobori in Japan in 1963 and subsequent patents [16,17], and that of Allen K. Breed, who in 1967 complemented Kobori's concept with the necessary mechanical crash detection sensor that deployed the airbag in less than 30 msec, sufficiently below the threshold value for effective airbag inflation in a collision. Sodium azide was used for the first time instead of compressed air during the airbag deployment. Amongst other related inventions, Breed also secured amongst others, US Patent 5,071,161A on airbags that used two layers of fabric and were vented in such a way that after a passenger came into contact with the airbag, some gas was allowed to escape, providing a safer, less rigid cushion [18].

Airbags were first introduced in passenger cars in the USA in 1971 by Ford (Mercury models) [19], followed by GM who provided frontal airbags as an optional extra between 1974 and 1976 [20]. In spite of GM's $80 million investment in the new development programme, airbags were not readily accepted by consumers. Later, with the implementation of the FMVSS in 1984, the market prospects for airbags improved in the USA, and there was an increase in the number of cars equipped with a driver airbag and a front passenger airbag, along with seat belts.

Funded research in the USA for airbag technologies related to air and spacecraft (and later personal and mass-transit vehicles) was initiated in the mid-1960s by the National Aeronautics and Space Administration (NASA) [21]. The development of these airbags for aeronautical applications arose from the original idea for a system that would restrain automobile drivers and passengers in an accident.

In Europe, Mercedes-Benz introduced an integrated airbag system in 1981 in Germany, wherein sensors would automatically pre-tension the seat belts to reduce the motion of the occupant during an impact followed by the deployment of the airbag. This integrated approach of coordinating the actions of seat belts and airbags is now a common feature in all safety restraint systems. Driver and passenger airbags were first introduced in 1987 in the "Porsche-944 Turbo" as standard safety equipment. However, airbags were not adopted in family cars across Europe until the early 1990s.

By the end of the twentieth century, almost all car makers in the USA and Europe had introduced airbag restraint systems in their cars, and since then, side-impact airbags are becoming regular features in mass-market cars in addition to frontal airbags; having stated this, however, airbags are still not standard equipment in some countries such as Russia.

The number of airbags can be varied depending on the car model and the requirement. A 1995 BMW concept car featured 12 airbags [22]; more recently, in Europe, BMW has introduced a head protection device, an inflatable tubular structure (ITS) sometimes described as "the sausage" and a side-impact airbag in addition to the frontal airbags. The world's first side-impact airbag (from Autoliv) was installed by Volvo during June 1994. Volvo was also the first original equipment manufacturer (OEM) to introduce an inflatable curtain, which was held inside the headliner and covered the length of the car interior. Three different head protection systems, namely, the combined head and thorax bag (HAT-bag), the ITS and the inflatable curtain were also introduced by Autoliv.

The first-generation airbags in 1970s were neoprene-coated nylon airbags, which were also adopted in late 1980s and early 1990s [23]. These airbags were made from either 420 or 840 denier nylon yarn. In second- and third-generation developments, lighter weight and more pliable fabrics were needed, and to meet the requirements, lower weights of neoprene coating add-on were applied and light-weight silicone-coated fabrics were introduced. Airbag construction in the mid-1990s focused on cost reduction, pliability and permeability control. Present-day airbag designs focus on the use of uncoated fabrics due to their lower cost and reduced environmental impact in their manufacture.

1.3. Key driving factors

The usage of airbags has increased manifold since they were adopted in late 1980s. This can be attributed to the following key factors:

- Strict legislation is the first and foremost factor, particularly where it mandates the inclusion of both the driver and passenger airbags in vehicles.
- Consumer awareness on the amount of lives saved by airbags.
- General increase in concerns for safety.
- Development of airbags for side impacts and rollovers.
- Improvements in technology leading to sophistication of systems.
- Competitive dynamics.

1.4. The market for airbags

Over recent years, consumer acceptance and demand for airbags around the globe has grown and the technology has changed to address new standards and challenges. The extended service life, reduced package size, reduced cost and improved occupant safety have been achieved primarily by new designs, use of advanced materials and methods.

The companies employed in the manufacturing and supply of airbags around the world include Delphi, Autoliv, TRW Automotive, Toyoda Gosei (TG), Takata and others. The global market share of these companies is represented in Figure 3.

The changes currently underway in the airbag market are the following:

- Continued growth of side-impact airbags in North America, Europe and Asia.
- The airbag market is still in its growth stages in South America, Eastern Europe, South East Asia, India and China.
- Availability of new raw materials and efficient fabric production technologies are helping to reduce weight and improve the packability.
- Newer coating applications with improved performance are a major contributor to this trend.
- Cheaper production facilities in developing countries have led to the mass production of airbags in these areas and subsequent distribution to other parts of the world.

1.5. Regulatory specifications

Legislative actions are the major drivers for the proliferation of airbag systems in passenger vehicles and they will be influential with regard to new developments. The

Figure 3. Global market share of airbag manufacturers.

following section outlines the key regulations followed in the USA, Europe and other countries.

1.5.1. US regulations

The US government amended the FMVSS 208 (the landmark standard from NHTSA) on 11 July 1984 [24] specifying that cars produced in the USA after 1 April 1989 had to be equipped with a passive restraint for the driver, with a phase-in to compliance starting with 10% for 1987 models, 25% for 1988, 40% for 1989 and 100% by 1990 [25]. Initially, some manufacturers elected to use automatic three-point safety belts to meet the requirement. A petition by the automobile manufacturers led to the right to gain compliance through installation of a driver side airbag and a manual three-point safety belt on the passenger side up to the mid-1993s. Subsequently, FMVSS 208 has gone through several revisions [24] and has also been broadened to cover additional vehicle classes.

The use of airbags and safety belts was also stimulated by the NHTSA. For example, the Transportation Equity Act for the 21st Century (TEA-21), directed the NHTSA (in 1998) to deal with the issue of smart airbags. This mandate required all vehicles to use smart airbags by 2006. However, NHTSA ultimately decided to roll out the smart airbag mandate. As per the current rule, airbags and safety belts must be installed in all passenger cars, light trucks, vans and multi-purpose vehicles.

1.5.2. European regulations

The United Nations Economic Commission for Europe (UNECE or more commonly ECE) works to harmonise traffic rules and, through the establishment of its Working Party on Road Traffic Safety in 1988, it has worked to improve road safety not just across Europe, but more widely as well. In the United Kingdom and most other countries in Europe, however, there is no direct legal requirement for new cars to feature airbags. Indeed, airbags were uncommon in European family cars even in the early 1990s. The first European car to feature an airbag appeared in 1992, in the face-lifted "Ford Escort MK5b" model. Subsequently, within a year, the entire Ford range had at least one airbag as a standard safety device.

The European New Car Assessment Program (Euro NCAP) encourages manufacturers to take a comprehensive approach to the occupant safety. Established in 1997, Euro NCAP is composed of seven European governments as well as motoring and consumer organisations in every European country. Euro NCAP organises crash tests and provides motoring consumers with an independent assessment of the safety performance of some of the most popular cars sold in Europe.

The overall safety rating is composed of scores in four areas such as adult protection, child protection, pedestrian safety and safety assist. Hence a good vehicle safety rating can only be achieved by combining airbags with other safety features, a factor perhaps in ensuring that new cars in Europe are now equipped with at least two airbags as standard.

1.5.3. Regulations in other countries

Some countries outside Europe also adhere to the ECE vehicle and equipment regulations rather than the US FMVSS. As per the ECE standard, airbags are generally smaller and inflate with less force than for the USA. In most Asian countries, there is no direct legal requirement for new cars to use airbags.

There are strict regulations in Australia in the use of airbags in the cars as a supplementary restraint to mitigate the injury consequences of serious crashes [26]. The Australian Design Rule for frontal occupant protection mandates the manufacturers to achieve the given safety standards in relation to head, chest and upper leg injury. Hence, Australia has high airbag usage and seat belt wearing rates. In addition, the airbags in Australian cars are generally smaller and set to trigger at higher road speeds than in US vehicles, and their airbags are consequently less likely to fire unnecessarily for the same reasons. There have been not many cases of major injuries in Australia caused by inflating airbags, such as those reported in the USA. Australian users are cautioned, nevertheless, to avoid the possibility of injuries by always restraining infants and children in approved restraints in the rear seat.

2. Types of airbags

The major application of airbags is in automobiles to reduce the severity of crash, but in addition, there are several other different applications of airbags, which are also discussed in the following section.

2.1. Airbags in automobiles

The airbags in automobiles are located in various strategic locations to mitigate the impact of a crash. The average number of airbags per car is increasing constantly and it has reached two-digit numbers in some of the models. The more recent airbag systems are called smart systems as they only deploy when it is necessary. They measure the passenger mass, severity of the crash and are activated through several phases, or are not activated at all if there is no passenger in the seat, or if the passenger is not buckled up or if the occupant is a child. These modern airbags can be classified on the basis of their location in the passenger car such as frontal airbags, side-impact airbags and its variations, centre airbags and knee airbags.

2.1.1. Frontal airbags

Generally, the frontal airbags are housed within the steering wheel, dashboard or other similar interior panels of a vehicle, and are covered by a trim cover panel which covers the compartment that contains the airbag module [27]. The frontal airbag construction and design differs depending on the type of the automobile. These airbags deploy in about 50 msec, which is half the time required to blink an eye. It has been reported that the airbags on driver and passenger sides require about 1.5 and 3.0 m^2 of fabric, respectively. These airbags can be primarily classified into two groups depending upon their placement in the vehicle, such as:

- Frontal driver's airbags.
- Frontal passenger's airbags.

The driver's airbag (Figure 4) with cushion sizes ranging from 30 to 60 L is an integrated part of the steering wheel system. The driver side airbag is generally designed to protect an adult, whereas the passenger side airbags are designed to protect a range of

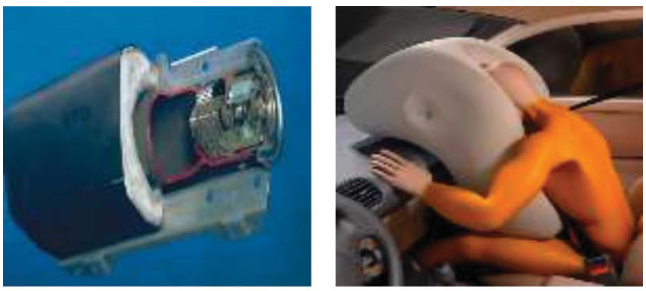
(a) (b)

Figure 4. Driver airbags: (a) before deployment in the steering wheel and (b) after deployment.

human body sizes, shapes and weights. The typical dimension of a driver side airbag is 714 mm (diameter) × 152 mm (deep) [28].

The passenger's airbag (Figure 5) is mounted in the dashboard on the passenger side with variable sizes ranging from 90 to 150 L. The passenger airbag reduces fatalities by approximately 20% (for belted front seat occupants) in frontal crashes. Additional features in frontal airbags such as active venting or special out-of-position (OOP) sensors make it possible to customise the airbag deployment for varying crash scenarios and passenger sizes.

Some variants of the designs involve frontal airbag systems for convertible-type vehicles to protect an occupant from striking the A-pillar of the vehicle in oblique frontal impacts [29], dual-section airbags for the protection of the chest which are mounted on the upper face of the instrument panel in front of the passenger seat [30] and front airbag modules mounted in the A-pillar [27]. The cover panels of the frontal airbags are typically made of rigid plastic and are configured to open by the pressure of the deploying airbag. In most cars, the cover is decorated so that the airbag remains invisible until deployed. During the airbag deployment, the cover is retained in at least partial attachment to the vehicle to prevent its free flight into the compartment and causing injuries.



(a) (b)

Figure 5. Passenger airbag: (a) before deployment and (b) after deployment.

Figure 6. Side torso airbag.

2.1.2. Side-impact airbags

Side-impact airbags are becoming popular as it is found that side collisions cause about 20% of the driver fatalities (second to the frontal collisions) due to the head injuries which occur as the driver's head strikes the hood or window sill or B-pillar of the car [31,32]. A survey has shown that the car driver death risk in driver-side crashes was reduced by 37% using side-impact airbags [33]. The side-impact airbags are designed to keep the occupant away from the impact zone and reduce the blow from the intruding side of the vehicle [34,35]. Since the occupant is kept away from the intruding vehicle side, protection of the head is improved. However, for more adequate head protection, special airbags are required.

Side-impact airbags are typically installed in the backrests of the front seats or behind the door trim and inflate between the seat occupant and the door [36,37]. The advantage of having the airbag module mounted in the backrest is that it will move with the seat and, therefore, gives optimal protection for variable sizes of occupants. The airbag can deploy either through a visible cover or burst through the stitching in the backrest. The side-impact airbags should deploy at the biomechanically appropriate areas of the body. The occupant's shoulder and pelvis are the most appropriate areas for biomechanical loading and the loading on the thorax should be minimised [38]. Although side-impact airbags reduce the injuries in side impacts, they also have shown to cause some injuries to the occupants [39,40]. There are two major types of side-impact airbags commonly used in modern cars, namely, side torso airbags and side curtain airbags.

2.1.2.1. Side torso airbags. The side torso airbags (Figure 6) are designed to reduce the risk of injury to the pelvic and lower abdomen regions [41]. These are usually located in the seat and inflate between the occupant and the door.

2.1.2.2. Side curtain airbags. Side-impact crashes at intersections account for approximately 22% of all major crash types where people are killed or seriously injured; side curtain airbags (Figure 7) or the inflatable curtains are a recent development in the airbag industry to mitigate their effect. They deploy from the roof/headliner above the doors to protect the occupants' (both front and rear) heads in side and rollover accidents. They form a cushion between the occupant and the window to protect the head from striking rigid objects such as the car itself or even trees or poles. The side curtain airbags on vehicles more prone to rollovers will deploy when a rollover is detected by sensors

Figure 7. Side curtain airbag.

instead of being activated by the actual collision. More recent side-impact airbags include a two-chamber system: a firmer lower chamber for the pelvic region and a softer upper chamber for the thoracic region [42–44].

The side curtain airbags will in effect become mandatory by federal law in all new vehicles sold in the USA by model produced in the year 2013 [45]. The installation rates of these airbags in new vehicles exceeded 70% in both North America and Europe. Similarly, the use of side curtain airbags has increased significantly in Australia. The number of new vehicles sold in Victoria (Australia) fitted with side curtain airbags has risen from 24% in 2006 to 64% in early 2011 [46]. The analysis of side curtain airbags showed (1) 51% reduction of injury to all body regions and (2) 61% reduction of injury to the head, neck, face and thorax [47,48].

Autoliv's patented inflatable curtains cover the entire upper part of a vehicle's side, cushioning the heads of all passengers seated on that side. It can be designed to protect one to three rows of occupants as per the vehicle design. Research conducted in the USA has estimated that side curtain airbags can reduce driver deaths in the event of a side-impact crash by about 40% [33]. Without these, there is little protection to the head from striking the side of the car or other external rigid objects like trees or poles.

Two main types of inflatable curtain designs are produced today. The first type is designed to absorb the energy of a direct side impact, whereas the second type can absorb energy up to several seconds in rollovers and in the case of another impact. The second type requires the airbag to retain pressure, which is accomplished by using a sealed cushion. In addition to the above types of side-impact airbags, there are some other variations of side-impact airbags depending on the protection area and type of the vehicle, which are discussed in the following section.

2.1.2.3. Thorax side-impact airbags. These airbags usually have a volume of only 8–12 L to make them as gentle as possible but still efficient enough to provide required protection [45]. The thorax side-impact airbag (Figure 8) inflates four times faster than the frontal airbag [49]. The thorax side-impact airbag is inflated at a certain crash threshold, usually corresponding to a speed of the impacting vehicle of more than 15–20 km/hr. Many convertible vehicles use head–thorax airbags for side-impact protection, which work in a similar way to the thorax side-impact airbag module but offer combined head

Figure 8. Thorax side-impact airbag.

and thorax protection in side-impact collisions for one occupant and are often used where the inflatable curtain (which provides protection in rollovers) cannot be mounted. It has been shown that the combination of a side curtain airbag and a thorax side-impact airbag are highly effective in reducing deaths and injuries in a crash [48].

2.1.2.4. Pelvis–thorax airbags. These airbags are designed to reduce the risk of injury to the pelvis and thoracic regions [50,51]. To achieve improved protection, the airbag's coverage area is extended by adding a cell, which is inflated to a higher pressure in order to distribute the load more efficiently over the thorax and pelvis parts of the occupant's body. This concept takes advantage of the pelvis' ability to take higher loads, while it limits pressure on the sensitive thorax–abdomen area. As the distance between the occupant and the car's stiff parts is small, this side-impact airbag deploys very quickly (within a few milliseconds), so that it will be in its protective position as early as possible in the crash. The pelvis–thorax airbag is located in the backrest frame of the car seat as shown in Figure 9.

2.1.2.5. Head–thorax airbags. Head–thorax airbags work similar to a thorax module and offer a combined head and thorax protection in side impacts to the occupants [50,52]. They are often used where the inflatable curtain (which provides protection in rollovers as well as for near seat occupants) cannot be mounted, such as in convertible cars.

2.1.2.6. Door-mounted airbags. Autoliv Inc., the largest automotive safety supplier, has developed a specially designed door-mounted inflatable curtain (DMIC) for convertible vehicles. This airbag is made up of a multitude of small cells in three layers similar to a beehive. This ingenious structure provides a high level of stability as a result of which it can be used in different situations, such as rollovers, since the structure is strong enough to hold the occupants securely inside the vehicle in many types of severe accidents. These

Figure 9. Pelvis–thorax airbag.

airbags are mounted in the door with the inflators and deploy in the event of a crash through various openings [53,54].

2.1.2.7. Rollover airbags. Rollovers are crashes involving vehicle rotation of at least one-quarter turn ($\geq$90°) about a lateral or longitudinal axis [55]. Although about 3% of all the crashes are rollovers, they account for 33% of the crash-related deaths [56]. During rollovers, vehicle movement involves deceleration along a horizontal plane, vertical acceleration and deceleration combined with rotational acceleration and deceleration. After rollovers, the vehicle may come to rest either on the side or upside down, on the roof or upright on all four wheels. During a rollover, the ejection of occupants causes most injuries and fatalities as most people killed are those not wearing safety belts to hold them in place [57]. Rollover airbags are side-impact airbags, which protect the occupants from ejection and injury during a rollover crash. In addition, they protect drivers' or passengers' heads during side-impact crashes. Only some of the side-impact airbags are designed to deploy as rollover airbags, but not all.

If a rollover is detected by the sensing unit, the rollover airbags are triggered and the safety belt retractors remove slack from the safety belt and position the occupant firmly in the seat. In several instances, the sensing unit can determine an imminent rollover when the roll angle is very small and all four wheels are still on the ground. Most of these airbags deploy downwards from the overhead roof rail, close to the side windows. Unlike other side-impact airbags, when rollover airbags are deployed, they stay inflated longer to help protect the heads of the occupants. In addition, they keep the occupants of the outboard seats from being ejected from the vehicle. The combination of rollover airbags and properly worn safety belts can significantly reduce the chances of ejection from the vehicle.

2.1.2.8. Combined torso and curtain airbags. Researchers on airbags describe the use of combined torso and curtain airbags (Figure 10) for the protection of both the torso and the head of the occupant [39,58]. The majority of the combination airbags are activated

Figure 10. Combined torso and curtain airbag.

from the seat or from the door or some from the ceiling. For example, US Patent 8,025,309 B2 [59] describes an airbag mounted on the ceiling of the car to restrain the head of the occupant. The airbag had an extended portion from the main body in downward direction to restrain the torso of the occupant. A tether was coupled to the vehicle frame and was used to control the deployment angle of the main airbag and the extended portion. These airbags are claimed to offer good protection to both head and body in side impacts. However, these designs are less effective than rollover airbags in rollover crashes. The side-impact airbags without the combination of head and torso designs only protect the chest and thorax area, not the head.

2.1.3. Centre airbags

Automobile manufacturers around the world have made great efforts to address the safety issues of the occupants, first focusing on the front seat and subsequently on the back seat. Recently, Toyota has introduced the first rear-centre airbag (Figure 11, a) that deploys from the ceiling during a side impact to minimise the injuries when occupants collide with each other [60]. Hence, the airbag can reduce the severity of secondary injuries in a

(a) (b)

Figure 11. The centre airbags: (a) rear-centre airbag and (b) front-centre airbag.

side impact. This airbag is designed not to deploy if the centre position of the rear seat is not being occupied.

Starting from the 2013 model year, GM has planned to install the world's first front-centre airbag (Figure 11, b) in its medium-sized vehicles [61]. The new front-centre airbag, co-developed with Takata Corporation, Tokyo, Japan, is a tethered tubular airbag located between the two front buckets. The airbag will deploy from the right or left side of the driver's seat to protect the driver in side impacts. The airbag will provide additional protection to a wide range of body sizes and types. The airbag will avoid head-to-head collision within the car when both the front seats are occupied or other types of contact trauma and it is designed to help to stabilise the driver even if the other front seat is vacant and will provide some additional protection in rollover crashes.

2.1.4. Knee airbags

Knee airbags are designed to reduce the leg injuries and can be mounted on both the driver and passenger sides [62,63]; they aim to restrict the forward movement of the knee and leg to reduce injuries [64,65]. Although knee airbags are found mostly on high-end luxury automobiles, they are gradually becoming more common place in mid-level models.

From a retrospective analysis of front seat occupants involved in police-reported, tow-away frontal motor vehicle collisions conducted using data from 1995 to 2000 by National Automotive Sampling System (NASS), it was found that compared with unrestrained occupants, occupants restrained with an airbag only had significantly higher risk for all types of lower extremity fractures. Occupants restrained by either a seat belt alone or seat belt plus airbag had a lower risk of fracture. The authors considered that their findings support the need to consider developing accessory knee bolster airbags to prevent "submarining" or sliding under the airbag [66].

Knee airbags may include a fixed panel (known as a knee bolster panel), which is disposed in front of the knee airbag to provide a more rigid surface area than an airbag alone. Knee airbags are located below the steering column on the driver's side and below the glove box on the passenger's side (Figure 12). These locations may, however, interfere with other essential parts such as parking brake handles, switches, vents, speakers or other control units.

In open vehicle architecture, the amount of interior surface area to support a standard frontal airbag is much reduced. Hence, knee airbags are an important addition in these

Figure 12. Knee airbags in driver and passenger side.

Figure 13. Pedestrian protection airbag.

vehicles, but they add considerable cost and complexity to the system. However, incorporating the knee airbags into a low-mounted passenger side airbag system is claimed to be able to reduce the cost and provide higher interior space while maintaining the safety standard of airbag systems [67]. Knee airbags can also be used in conjunction with the head or torso airbags [68].

2.1.5. Pedestrian protection airbags

Recently, Volvo introduced the first airbag engineered to protect pedestrians [69]. When a pedestrian or cyclist approaches a Volvo-V40 moving between 19 and 50 km/hr, the radar sensors detect them and an alarm alerts the driver and brakes the car. Upon any impact, the rear edge of the bonnet (hood) rises 4 inches driven by a pyrotechnic charge and the airbag deploys to cushion the pedestrian or cyclist against the engine and the windscreen [70] (Figure 13). The airbag and bonnet, which pop up in milliseconds, are designed to prevent head injuries, the single biggest cause of pedestrian deaths. Of course, the incorporation of these airbags and its deployment system increases the cost of the car.

2.1.6. Other airbags

The different types of new airbag designs such as seat cushion, knee bolster (one type of which was mentioned in Section 2.1.4) and roof airbags are beginning to become part of the automotive market. The seat cushion airbag comprises a front seat cushion, which lifts the lower legs from the floor in a collision to eliminate the chances of bracing and minimising interaction with the intruding structure [71]. In addition, it provides a restraint for the pelvis eliminating the need for a full knee bolster [31]. The knee bolster is a small airbag, which provides additional benefits for the head and chest in frontal collisions by keeping the occupant in proper position while the conventional airbag deploys [72]. The roof airbag or head restraints aim to prevent head injuries. The head restraints can be in the form of a movable head rest that would come towards the driver or passenger's head due to the momentum during the crash [73]. The head restraints prevent the injuries of head and neck caused by the violent acceleration or deceleration of the vehicle. These restraint systems can be added to the seal of the window frame running from the instrument panel to the B-pillar [74].

2.2. Airbags in motorcycles

Different types of airbags are also used as safety restraint systems on motorcycles [75–77]. Organisations such as the Transport Research Laboratory (TRL), DEKRA Automotive and Honda Motor Co. are currently involved with the research and development, and production of airbag prototypes for motorcycles [76]. The first-stage motorcycle airbags were tested by the UK Transport Research Laboratory in the mid-1970s. In 1994, Van Driessche described ISO 13232, which specified the test and analysis methods for evaluation of rider crash-protective devices fitted to motorcycles [78].

Based on the analysis of crash data of motorcycle accidents showing that many injuries and fatalities occur when the motorcycle rider collides with another vehicle or the road or other objects after a frontal collision [79], Honda decided that motorcycle airbags should be designed so as to reduce the forward momentum of the rider and reduce the velocity at which the rider may be thrown from the motorcycle, thus reducing the severity of injuries to the rider colliding with another vehicle or with the road. An oversized "V"-shaped airbag was developed using tethering straps to anchor the airbag to the frame for support, a design which, they claim, offers increased stability when the rider comes into contact with it. Subsequently, in 2006, Honda Motor Co. introduced the first production motorcycle airbag safety system on its Gold Wing motorcycle after unveiling its airbag technology in 2005 [79].

In a severe frontal collision, the crash sensors mounted on the front fork of a motorcycle measure the change in the acceleration caused by the impact and convey these data to the electronic control unit (ECU), the same unit that centrally controls the motorcycle's engine operations. When the ECU determines it is necessary to inflate the airbag, it sends an electronic signal to the inflator, which instantaneously deploys the airbag (Figure 14).

A motorcycle may encounter a wide range of crash conditions and its attitude may vary significantly depending on the angle of impact with the object. Hence, the performance of the airbags should be thoroughly investigated prior to the installation. Honda used special motorcycle rider test dummies to provide data from sensors embedded in the dummy's head, neck, chest, stomach and limbs, to make it possible to estimate the extent of injuries from collisions over virtually the entire body. Computer simulations can also be used to create high-precision collision re-enactments that enable to analyse a broad range of crash conditions.

Figure 14. Airbag used in motorcycle.

Airbag suits have been developed for the Motorcycle Grand Prix riders. The airbags are connected to the motorcycle by a cable and deploy when the cable is detached from its mounting clip. The French manufacturer, Helite, is developing airbag jackets for motorcycle riders, snowmobile riders and horseback riders [80]. In addition to the above SRS, armoured airbags [81,82] and airbag vests [83] are also used to reduce the possibility of injury to important body parts such as the spine, chest, neck and major organs of the upper body when a motorcycle rider or a horseback rider is thrown.

2.3. Airbags in aerospace applications

Airbag technologies have been used by the aerospace industry for many years. The NASA and the US Department of Defense have incorporated airbag systems in various aircraft and spacecraft from as early as the 1960s. The primary objectives of these airbags are for occupant protection and in aircraft landing systems as discussed in the following section [84–86].

2.3.1. Occupant protection

In aircrafts, the airbags prevent passengers from striking the front seat, tray tables, side window, privacy walls or any other interior objects [87]. They are designed to lessen the impact of crashes to minor injuries. The airbags in most aircrafts are located in the back of each seat or in the seat belt. The front seat or bulkhead passengers in an aircraft do not have a seat in the front of them. Hence, the airbag can be positioned in the passenger seat belt. In a crash, the system rapidly inflates the airbag that runs the length of the seat belt from the buckle to the point where it enters the upper part of the seat or pillar [88]. Until recently, only two major airlines have provided seat belt airbags.

The US Army has incorporated airbags in its UH-60A/L Black Hawk and OH-58D Kiowa Warrior helicopter fleets. The cockpit airbag system (CAS) consists of frontal and lateral airbags and an ITS (on the OH-58D only) with an electronic crash sensor unit (ECSU). CAS is the first conventional airbag system worldwide for occupant injury prevention, designed and developed for aircraft and helicopter applications.

2.3.2. Airbag landing systems

Often, manned and unmanned aircrafts are required to land in a small landing space where no landing runway is available, either due to a planned recovery of the aircraft in such area or unexpected technical problems. Many aircrafts are provided with dedicated equipment such as parachutes and airbag landing systems in order to enable the aircraft to land in difficult areas or on sea. The parachutes are actuated at a given height above the ground and the airbags inflate a few moments before the aircraft hits the ground. The airbags help in shock absorption of the aircraft [89]. Other circumstances may require a soft landing for equipment being dropped from aircraft [90].

The first airbag landing systems in space exploration were used for the landing of Luna 9 and Luna 13, which landed on the Moon in 1966 [91]. The Mars Pathfinder Lander employed an innovative airbag landing system, supplemented with aero-braking, parachute and solid rocket landing thrusters [92,93]. This prototype successfully tested the concept of landing and the two subsequent Mars Exploration Rover Mission Landers employed similar landing systems [94,95]. Although, the Beagle II Mars Lander also

(a) (b)

Figure 15. Airbags for (a) protection against falls from heights and (b) protection against wheelchair overturns.

used similar airbag landing systems for landing [96]; the landing was unsuccessful for reasons which are not entirely known.

2.4. Airbags in other applications

Airbags have been used on military fixed-wing aircrafts such as the Escape Crew Capsule of the F-111 Aardvark. Airbags are being used to provide soft-landing capability for heavy military airdrops [90]. There has been the use of airbags in earthquakes, tornados and similar disasters [97]. They are also used for protection from incidental falls (from height or on the same level) caused by slipping or tripping and falls from wheelchair overturns, which are common phenomena associated with serious injuries due to the impact with the ground [98,99] (Figure 15). Similarly, fall and fall-induced injuries are very common among the elderly. Hip fractures of the ageing population account for the highest number of deaths among all the fall-induced fractures. To prevent the impact force from falling down, an airbag system has been designed which can be triggered in less than 0.3 sec using compressed carbon dioxide (CO_2) cartridges [100]. The systems consist of an airbag, a sensor, an inflator and a jacket. In the event of a fall, the sensor detects the fall and the airbag inflates to protect the user.

3. Manufacturing of airbags

The main elements of the airbag system are inflatable cushions, impact sensors, ignition system, propellant, mounting hardware and moulded covers. The manufacturing process of airbags involves several steps starting from the appropriate selection of raw materials to the final assembling of the whole airbag module. While designing airbags, the following requirements are essential [6]:

- Reduced cost.
- Satisfactory performance level.
- Precisely controlled air permeability.

Table 1. The requirements for an airbag module substrate.

Issues	Product development objective
Cost	To develop a substrate that would be less costly and easy to produce.
Flexibility	To develop a substrate that is more flexible than current coated fabrics and exhibits reduced pack height.
Permeability	To develop a substrate that will exhibit uniform and controlled permeability.
Packability	To develop a substrate that exhibits excellent packability.
Recyclability	A product that can be recycled as a cutting scrap at the end of its life cycle.
Performance	Performance as per the specification standards.

- Excellent seam integrity.
- Good ageing resistance.
- Excellent packability.

In the view of airbag module assemblers, the perfect substrate for airbags is uncoated fabric that performs as well as a coated fabric; inevitably, this leads to finding the best compromise. The manufacturers' objective, therefore, is to develop and engineer fabrics that would exhibit the best attributes of both the coated and the uncoated fabrics. The major properties affecting the airbag's effective performance are low, uniform air permeability and excellent packability. In addition, the cost of the final airbag module should be low in order to keep the overall vehicle cost down. Table 1 lists the essential factors to be considered while designing an airbag module.

This section will deal with the fibre, yarn and fabric types used, weaving, finishing techniques and assembling processes involved in the airbag manufacturing process.

3.1. Raw materials

The most important textile starting material for manufacturing airbags is the finished fabric. In addition to the fabric, the complete airbag module consists of inflator or gas generator, crash sensors and the ECU. The majority of commercial airbag fabrics are manufactured from multi-filament yarns of nylon 6,6. But other materials are used including polyester (PET), nylon 4,6, nylon 5,6, nylon 6 and also some other fibre types. As airbag fabrics are mainly prepared from thermoplastic synthetic fibres, they will melt if heated to a sufficiently high temperature or shrink if exposed to temperature above their glass transition temperature (T_g). The different types of raw materials used for airbag manufacturing are discussed in the following section.

3.1.1. Fibres

The fibres used for airbag fabrics should possess high strength, thermal stability and energy absorption capability, good ageing characteristics, coating adhesion and functionality under extremely hot and cold environmental conditions. The most widely used fibre type in airbag fabrics is polyamide [101], especially nylon 6,6 with linear densities ranging from 420 to 840 denier. Nylon 6,6 is a preferred material for manufacturing of airbags due to the following reasons:

Table 2. Specifications of nylon 6,6 fibres used for airbag fabrics.

Parameters	Nylon 6,6 (420 denier)	Nylon 6,6 (840 denier)
Filaments	68	140
Tenacity (g/d)	7.9	8.4
Elongation (%)	21	21
Shrinkage (% at 177 °C)	6.1	6.5
Melting temperature (°C)	256	256

- It has a high-strength-to-weight ratio, so sheer/lightweight fabrics made from nylon 6,6 can still be strong.
- Nylon 6,6 exhibits high elongation, which helps in the uniform distribution of stress along the circumference of the airbag during deployment.
- Taking its high strength and elongation together, nylon 6,6 is a tough material, well able to withstand the combined stresses and strains involved in airbag deployment.
- It has a satisfactorily high specific heat capacity, melting point and heat of fusion compared to other common synthetic fibres, making it suitable for exposure to hot weather conditions.
- It has a standard moisture regain of 4%, which may help in reducing burn injuries to the crash victims by providing higher quenching property for any hot particulate matter (emerging from the ignitor) that might break free from the inflator.
- As a commodity fibre, it is available at a sufficiently economical price for the airbag application.

The properties of nylon 6,6 fibres used for airbag fabrics are given in Table 2 [102]. Polyester (polyethylene terephthalate) is the second dominant fibre after nylon for airbag fabrics. Recently, there has been some research aimed at replacing nylon 6,6 with polyester [103–108], as was done for seat belt fabrics. Some of the airbags designed with polyester fabric showed superior mechanical properties, flexibility and packaging properties, whilst maintaining sufficient performance under severe conditions of high temperature and high humidity [105,109].

However, some of the properties that make polyester more appropriate for seat belts make it less appropriate for airbags. In the case of seat belts, the advantage of polyester is that it is much less hygroscopic (with a typical standard moisture regain of 0.25%) than nylon (standard moisture regain circa 4%). Therefore, polyester does not exhibit humidity-induced dimensional changes, and unlike nylon, which exhibits a high degree of elongation under high loading, it does not stretch to the same extent under tension,

Table 3. Comparison of nylon 6,6 and polyester fibres used for airbag fabrics.

Parameters	Nylon 6,6	Polyester
Density (kg/m^3)	1120	1390
Specific heat capacity (kJ/kg/K)	1.67	1.30
Melting point (°C)	256	256
Softening point (°C)	220	200
Energy to melt (kJ/kg)	589	427

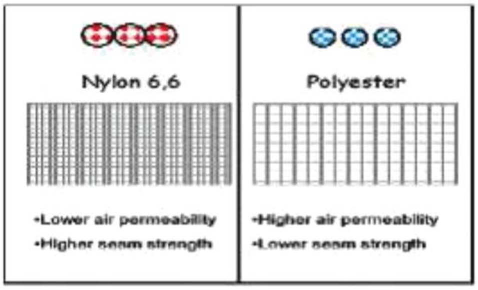


Figure 16. Comparison of fabric cover of nylon 6,6 and polyester.

characteristics that make polyester more suitable in seat belts than nylon. However, the operating conditions for airbag fabrics are different from those of seat belts, and nylon's particular properties, not least its low density, higher latent heat of fusion, superior ageing characteristics, higher elongation and toughness, become essential characteristics in its success as a fabric in airbag manufacture.

Table 3 gives a comparison of the properties of nylon 6,6 and polyester fibres used for airbag fabrics [102]. Although the melting points of both nylon 6,6 and polyester are same, the large difference in the latent heat of fusion results in about 30% more energy required to melt nylon 6,6. Therefore, in the event of an inflation that contains a pyrotechnic inflator, airbags of polyester are more susceptible to burn or melt. The lower density of nylon 6,6 results in airbags, which are at least 20% lighter than their polyester counterpart. Lower mass of the airbag is beneficial as the kinetic energy of the impact on the occupant is lower, which enhances the safety.

The difference in the density between the two polymers leads to polyester yarns being of higher denier or decitex (weight per unit length) than nylon 6,6, to generate the same filament diameter. This results in reduced fabric coverage for the same weight per square metre as illustrated in Figure 16. The use of polyester yarn results in a cushion fabric, which is more open to gas permeation. This reduces protection for the vehicle occupants from hot particulates from the airbag ignitor, and makes it more difficult for the cushion designer to control the bag deployment dynamics. In addition, since seam strength is strongly dependent on fabric cover factor, seam performance is negatively impacted with polyester. This is particularly important since leakage of hot gas is one of the principal concerns and the potential for an increase in leakage at the seam combined with a reduction in the thermal resistance is critical.

The airbag is expected to remain fully functional throughout the life period of the car. Nylon 6,6 is superior to polyester in terms of long-term property retention. Polyester suffers from an ageing effect with the influence of heat and humidity, which makes it unsuitable for airbag applications. A comparison of some of the important properties of the commonly used fibres for airbags with nylon 6,6 is given in Table 4.

In spite of the advantages mentioned above, nylon 6,6 has some disadvantages such as nylon is inferior to polyester in terms of humid heat resistance, light resistance (which should not pose problems to a concealed airbag) and shape stability [108].

Some of the other fibres proposed, although not used widely for airbag fabric, include polyamide fibres other than nylon 6,6 such as nylon 6 [110–115], nylon 12 [111,113–115], nylon 4,6 [110–115], nylon 6,10 [110], nylon 6,12 [110,114]; polyester fibres other than polyethylene terephthalate such as polytrimethylene terephthalate [110–114], polyethylene

Table 4. Comparison of properties of airbag materials with nylon 6,6.

Parameters	Nylon 6	Nylon 4,6	Polyester	Para-aramide
Melting point	↓	↑	→	↑
Strength	→	→	→	↑
Elongation	↑	↑	↓	↓
Heat resistance	↓	↑	→	↑
Cost	↑	↓	↑	↑

naphthalate [110,114], polybutylene terephthalate [110–113,115], aromatic polyester [112,113]; aramid fibres (copolymers of paraphenylene terephthalamide and aromatic ethers) [111–113]; vinylon fibres [110], acrylics [110], polyvinyl alcohol [115], polyvinylidene chloride [115], polyacrylonitrile [115], polyurethane fibres and polyolefin fibres [110,115]. In addition, research has been done on some uncommon fibres such as polyphenylene sulphide (PPS)-based fibres [110–113], polyether ketone (PEK) [110–113], polyimide fibres [110], cellulosic fibres including super-high-strength viscose rayon [110], carbon fibres [110], glass fibres [110], silicon carbide fibres [110], polyparaphenylene benzobisoxazol (PBO) fibres [111–113,115], ultra high molecular weight polyethylene (UHMWPE) [111–113] and alumina fibres [110].

Most of these synthetic fibres are thermoplastic in nature, which enables the fibre, yarn and eventually the fabrics to be set without causing chemical change under various conditions by the application of heat on a time/temperature basis. The shape heat-set into the fibre during manufacturing will be permanent unless the time and temperature are exceeded in subsequent processing where a new overriding "set" is introduced. The "heat history" of the synthetic yarns and fabrics provides useful information for process sequence, end-use applications and even quality problems in the fabrics.

3.1.2. Yarns

The basic building blocks for the airbag fabrics are yarns. Continuous filament yarns (false twisted and air textured) are generally used for the airbag fabrics. The earlier airbag fabrics were manufactured from coarser (about 940 dtex) nylon 6,6 filament yarns. The airbags in the most modern cars are being manufactured from finer nylon 6,6 filament yarns (from 50 to 850 dtex) [116]. The number of individual filaments in the yarn is important for achieving the desired properties. The use of finer filaments in the yarn results a fabric with lower air permeability. In addition, the stiffness of the fabrics produced from finer filament yarns is lower, which helps in easy packability. However, the tensile and the tear strength of yarns of finer filaments are lower.

The synthetic polymer filaments are produced by the extrusion of the molten polymer through a spinneret consisting of a series of fine holes. The shape, size and number of holes determine the fibre cross section, fineness and number of filaments in the yarn. Following extrusion, the filament yarns are gathered together, dried or cooled in an air flow, then wound onto bobbins for subsequent process. During the production process, the filaments are drawn or stretched to orient the molecules, which provides strength to the yarn and reduces the further tendency to stretch [117].

As discussed in Section 3.1.1, nylon 6,6 yarns are preferred to the polyester yarns for airbag manufacturing. As both the yarns are synthetic and thermoplastic, they are

Table 5. Yarn parameters used for airbag fabrics.

Yarn type	Fineness	Yarn tenacity	Elongation (%)	Shrinkage (%)
Nylon 6,6 [118]	350 dtex	60 cN/tex	15–30	< 6 (at 190 °C) (hot air)
Polyester [119]	330 dtex	60 cN/tex	>15	–
Polyester [120]	470 dtex	65–75 cN/tex	20–30	<1
Polyester, nylon 6, nylon 6,6, nylon 4,6 [121]	40–400 denier	5 g/denier	>30	–
Nylon 6,6 [122]	630 denier	9.3 g/denier	–	–
Polyester [122]	620 denier	5.1 g/denier	–	–
Polyester [123]	650 denier	8.5 g/denier	16	–
Polyester [123]	540 denier	8.5 g/denier	17	–
Nylon 6,6 [124]	100–800 dtex	5–11 cN/dtex	15–35	4.5–5 (boiling water)

lubricated at various stages of processing to reduce static electric charge build-up and thereby improve the efficiency of winding, warping and weaving. These lubricants are removed subsequently by suitable processes.

The important yarn parameters for airbag fabrics are yarn strength, elongation and uniformity. The multi-filament yarns used for airbag fabrics should have high tensile strength with low coefficient of variation (CV) to improve the strength of airbags. High CV values of yarn strength will negatively affect the fabric strength. High elongation is good for proper deployment of the airbag, which enables uniform stretching of the fabrics. Some of the yarn parameters used for airbag fabrics is listed in Table 5.

3.1.3. Fabrics

Almost all of the airbags manufactured worldwide are made from woven fabrics consisting of two sets of threads interlacing at right angles to each other composed of nylon 6,6 yarns. The other structures used are knitted (formed by the interlacing of threads at a variety of angles to each other) and non-woven (produced directly from fibres using some bonding or needling process). The airbag fabric is required to have the following properties:

- High tensile strength.
- High tear and bursting strength.
- Good heat stability.
- Good ageing characteristics,
- High energy absorption features.
- Good coating adhesion.
- Functionality in extreme hot and cold conditions.
- Good packability.

The early stage airbag fabrics were coarse and heavy, and the surface of the airbag made from these fabrics was coated with a relatively heavy neoprene coating [28] resulting in a coated airbag fabric with a weight as high as 500 g/m^2. In addition, the coated surface was heavily covered with talc to facilitate handling and packaging as well as to prevent the possibility of blocking/sticking between fabric layers during folded storage of the airbag. Not surprisingly, the early airbags needed a large module for storage and

Table 6. Material requirements for various types of airbags.

Component	Issue	Material requirement	Material choice
Module	Smaller pan	Thin gauge, lower pack volume	420 denier or less, coated/ uncoated
Bag type	Driver	Coated face (minimum)	Coated fabric
	Passenger	Uncoated	Uncoated fabric with controlled permeability
	Side-impact	Coated/uncoated, tight permeability control	Good integrity
Inflator type	Hot	Good insulation, burn resistance	Coated fabrics, 630 denier or greater/uncoated
	Cooler	Good insulation	Same
Inflator aggressiveness	High slope	Excellent seam strength	Coated fabrics
	Normal slope	Permeability control	Coated fabrics

deployment. Subsequently, fabrics were developed to be of lighter weight, cheaper and with improved performance.

3.1.4. Other components

Other components for an airbag module include crash sensors, inflators and the ECU. These components are fabricated or sourced from external suppliers and integrated to the airbag module. As the major parts in the crash sensors and the ECU are electronic, they are fabricated by the electronic companies. The inflators are sourced from appropriate chemical companies. The whole airbag module is prepared by assembling the cushion together with these components. The requirement of different types of airbags varies depending on the type of the airbag, inflator and other assemblies (see Table 6). The detailed manufacturing and assembling process are discussed in the following section.

3.2. The manufacturing process

Woven fabrics are the dominant materials in airbag cushion manufacture. The manufacturing of woven airbag fabrics starts with appropriate yarn selection followed by the preparatory processes, weaving, greige inspection, chemical finishing (scouring, heat setting, coating or calendering) and final inspection. The following section describes the manufacturing processes used for airbag fabrics in more detail.

3.2.1. Preparatory process

The preparatory process involves yarn preparation or warping, weaving beam preparation, entering the warp into the loom and finally the weaving. Any fault left during the preparatory process is transferred to the fabrics. Hence, the preparatory process should be done carefully to produce good-quality fabric. During the yarn preparation or warping, the yarn packages are mounted in a creel and drawn individually onto a beam.

The individual warp threads are placed side by side in the beam as a continuous sheet with lengths of 3000 m or higher depending on the weave density, yarn type and count. In many instances, sectional warping is preferred due to its quality and versatility. In sectional warping, the desired number of warp threads is put on a drum in several sections, which are subsequently transferred to the weavers beam used in the loom. The correct build-up of the yarn sections across the width of the drum is essential for the production of a good-quality fabric. The individual ends must then be drawn through the heald eyes in the heald frame of the loom in the correct sequence before weaving can commence. Some yarns are applied with special ingredients (size) during the preparation of the weavers beam (discussed later on).

3.2.2. Weaving

The major requirements for airbag fabrics include low thickness, high tensile strength, high resistance to tear, high anti-slip properties of the seam, good dimensional stability, resistance to ageing, defined and uniform air permeability and product reliability at least for 15 years – all characteristics which can be achieved with appropriately constructed woven fabrics.

The airbag fabrics should be of high quality and free from defects; there are stringent tolerances. Among the properties mentioned above, the air permeability of the fabrics must be precisely controlled and consistent across the whole dimension of the airbag. The air permeability of the airbag fabric should be as low as 1 cubic foot per min (CFM) at a pressure drop of 0.5 inches of water [119]. Control over the weaving process plays a vital role in achieving high-quality and defect-free fabrics. Generally, airbag fabrics are woven on rapier weaving machines [125–127], which are proven to be able to produce excellent fabrics with zero defects and are successful in achieving high weave densities. A high weave density is necessary for the structural integrity of the airbag, and its ability to withstand inflation and collision forces during deployment.

Some manufacturers use water-jet looms rather than rapier looms [128]. The advantage of a water-jet loom is that it can eliminate the need for the extra process of sizing in weaving yarn preparation, if yarns of appropriate quality are selected [129,130], whereas weaving yarns on rapier looms without any sizing can result in unacceptable yarn damage from the heat generated by abrasion with the heald wires during weaving. Since there is no size applied to the yarn in water-jet weaving, the process of scouring/desizing is also eliminated. Furthermore, the productivity of rapier looms is typically lower than with water-jet weft insertion. In spite of their advantages, the water-jet looms have certain disadvantages in that they can create wide variation in the air permeability of the fabrics across their width; they show a tendency to blossom the fabric, particularly at the edges which leads to variability in air permeability. The greige fabrics produced by the water-jet loom must be dried after weaving to remove the water left on the fabric and prevent the growth of mildew. The changeover process when a different fabric is needed to be woven in a water-jet loom is also more complex than for rapier looms. Water-jet looms are also less flexible with respect to on-loom constructions and the fabric quality is inferior compared to rapier.

In addition to rapier and water-jet looms, air-jet looms are also used for airbag fabric production [131,132], not least because the productivity of air-jet looms can be higher than the rapier looms. One of the American airbag suppliers, “Allied Signal”, uses about 400 picks per min in airbag manufacture in their rapier looms, whereas 600 picks per min is able to be achieved in their air-jet looms.

Airbags are most often made from plain woven fabrics [101,133,134] predominantly made of nylon 6,6 multi-filament yarns with counts ranging from 235 to 940 dtex [135]. In addition, there are some published work on other weaves such as basket [119], ripstop [136], combinations of twill and basket [137], hopsack and fancy weaves [138]. The type of weave and weave count affect the air permeability, tensile strength, biaxial properties and physical bulk of the airbag fabrics. The plain weave fabric, for example, shows substantial increases in its air permeability when subjected to tensional forces. To avoid this problem, a combination of different weaves such as twill and basket can be used [137].

It is a well-known fact that for achieving higher tensile strength, the number of warp and weft threads should be increased. Hence, airbag fabrics are generally woven very densely, which is a challenging task to achieve. The warp and weft yarns are generally of the same composition and fineness. The warp and weft density or the weave count of the fabric can be the same or there can be a slight difference in the values. It is important to have a balanced fabric (same warp and weft density from same yarn), which can result similar strength in both warp and weft directions. This property is essential as the airbag is radially symmetrical with no preferential direction of stress.

For a one-piece airbag, however, the situation may need to be different, as gas insertion takes place via a gas lance and the hot gas particularly stresses regions around the lance. To overcome incidences of tears in this region, the one-piece airbag may be woven with reinforced areas where these are required for effective airbag operation, whilst weaving a more lightweight structure where it is not. Flexibility in the reinforced areas of the fabric can be maintained by alternately weaving in a weft yarn of 25% greater dtex value in place of the usual reinforcement yarn, for example, a 470-dtex reinforcement yarn alternating with a 350-dtex reinforcement yarn. For regions where the extra reinforcement is not required, the reinforcement yarn is allowed to float [135].

A series of tight airbag fabrics with 0.27–0.31 mm thickness was produced by Kovačević et al. [139] using nylon 6,6 multi-filament yarn. The same sets of warp and weft yarns of high tenacity and low CV were used to prepare the fabrics in order to achieve high fabric strength with lower variability. In addition to the tensile strength, the tear strength and ball bursting strength were also measured to evaluate the performance of the airbag during deployment. In US Patent 5,093,163, a balanced fabric was prepared by using the same warp and weft yarns with identical thread spacing [118].

The warp yarns for airbag fabrics woven in rapier looms need to be sized before weaving. The sizing material prevents the warp yarn from damage caused by rubbing with other yarns and the metallic eyes within the heald frame. The yarn is coated by passing it into the sizing material, through squeeze rollers and then over a series of cooling rods. The common sizing materials used on yarns intended for airbag fabrics are polyacrylic acid, polyvinyl alcohol, polystyrene and polyacetates. Other compounds can be added in this stage to improve the functionality of the fabrics. Grafting compounds can also be added, to make pliable fabrics and prevent excessive fraying.

Although, sizing is essential in enhancing the mechanical integrity of the yarn during weaving, the sizing chemicals may not be compatible with the airbag coating material. Hence, these chemicals are removed by a desizing and/or scouring process followed by washing and drying operations. These additional processes increase the overall production cost of the airbag fabrics and can lead to fabric shrinkage. It is therefore attractive to avoid having to use the sizing process, if at all possible, by suitably selecting the yarn parameters, weaving machine types and settings. For example, the water-jet loom has been used for weaving airbag fabrics using the yarns without any sizing [140]. The warp tension was increased from 60 to 80–95 g/inch to increase the weave density significantly.

Figure 17. Airbag fabric inspection after weaving.

During weaving, as the weaving progresses, the warp tension can change gradually and this affects the fabric quality. To avoid this problem, tension is precisely controlled by very accurate sensors with an accuracy of 1 cN per warp end. The filling yarns or wefts should be free from any knots, and their presence is monitored by optical devices in combination with the computer. The atmospheric conditions (i.e. the temperature and humidity) in the weaving shed need to be accurately controlled. The selvedge is an important part of the woven fabric as it keeps the weft taut, but it does not play a part in the airbag; hence it is trimmed off, baled and recycled.

In rapier looms, features such as full-width temple, knot-stop motion, weft yarn feeder, controlled bolt clamp, selvage rollers, controlled weft yarn break, take-up roller with rubber coating, selvage sealing devices and programmable microprocessor can be incorporated to reduce loom stoppages. The Picanol specification for their rapier looms states that airbag fabrics can be woven successfully with loom stoppage rates below 1 stoppage per 10^5 picks [141]. The fabrics can also be woven in double width on projectile weaving machines with configurations such as cam motion, electronically controlled warp let-off, warp tensioner, D12 projectiles with large clamping surfaces, bright polished and stainless reeds, full-width temple across entire fabric width and selvage sealing device.

Some of the features of Optimax (rapier) and Omniplus (air-jet) from Picanol used for airbag weaving include reinforced backrest, reinforced cloth take-up for high warp tension (typical for airbag weaving), laser warp stop motion and full-width temple. The auto-speed system in Omniplus adjusts its speed for optimum quality, irrespective of the yarn characteristics throughout the beam.

The inspection of the airbag fabric quality during weaving is essential, since this affects the final performance of the airbag. The final inspection of airbag fabrics is done on a viewing table with proper arrangement of lights (Figure 17). A number of faults are checked and rectified with appropriate methodology. Fabrics are rejected if they contain any major defects or minor defects beyond the specification. For example, the fabric is rejected if faults of 0.5 mm^2 area or higher are present at more than three places per 100 linear metres of the fabric.

Commercially, different constructional parameters for airbag fabrics are used by different industries. There have been numerous investigations on the airbag fabrics with varying construction. Table 7 indicates the constructional parameters used by several researchers for weaving the airbag fabrics.

Table 7. Specification of the airbag fabrics used by various research groups.

Research group	Material	Weight (GSM)	Weave	Epcm	Ppcm	Thread linear density(filaments)	Coated/ uncoated
Behera & Goyal [142]		150–240		41–75	41–75	220–700 denier	Coated
Partridge & Mukhopadhyay [143]	Nylon 6,6		Plain	14	14	470 dtex	
	Nylon 6,6		Plain	16.8	16.8		
Keshavaraj et al. [144]	Nylon 6,6		Plain	72	46	420 denier	
			Plain	42	42	630 denier	
			Ripstop	32	32	840 denier	
	Polyester		Plain/uncalendered	42	42	650 denier	
			Plain/calendered	42	42	650 denier	
Kovačević et al. [139]	Nylon 6,6	229–292	Plain	18–21	14.5–18.8		
Bloch [101]	Polyamide	280	Plain	16	34	470 dtex	Uncoated
Keshavaraj [145]	Nylon 6,6	220		20	19.7	420 denier	
Bower et al. [140]	Nylon 6, Nylon 6,6, polyester, polyacrylonitrile		Plain	46	46	420 denier	
				38	38	630 denier	
				33	33	840 denier	
Krummheuer et al. [118]		180–243		27	26	235–470 dtex	Uncoated
Bowen et al. [137,146]	Nylon 6,6	200	Twill + Basket	24.8	25.6	315 denier	Uncoated
		285	Twill + Basket	18.1	18.9	630 denier	
		235	Twill + Basket	22	22.4	420 denier	
Thornton et al. [119]	Polyester		2×2 Basket	19	19	400–600 denier	Uncoated
Swoboda et al. [147]	Polyester	200	Plain, ripstop	26	26	280–450 dtex	Uncoated
Wang et al. [148]	Nylon 6,6		Plain	21.7	21.7	470 dtex (72)	
	Nylon 6,6		Plain	25.6	25.6	350 dtex (72)	
Debenedictis & Schmitt [149]	Polyester	221	Plain	18.9	16.9	467 dtex	Coated
Kim et al. [106]	Polyester		Plain	20.8	20.8	460 denier (60)	Coated
Schmitt & Debenedictis [150]	Polyester	215	Plain	18.5	18.5	490 dtex	Coated
	Nylon	214	Plain	18.5	18.5	470 dtex	Coated

In order to achieve the critical performance requirements of airbag fabrics, Behera and Goyal [142] applied artificial neural networks in engineering the airbag fabrics, which overcomes the major drawbacks of conventional fabric engineering. The airbag fabrics were manufactured with utmost precision which achieved the specification with minimal variation.

3.2.3. Knitting

Although the woven structures predominate in airbag fabrics, research has been done on knitted structures [116,151–155]. The knitted fabrics are prepared by forming loops symmetrically above and below the mean path of the yarn, whereas in weaving, one set of threads runs parallel to the length (warp) and the other set runs crosswise (weft). The yarn (s) in the knitted fabrics, therefore, follows a meandering path (course), which allows the fabric to be stretched easily in different directions. This provides knitted fabrics much more extensibility than the woven fabrics. Often, the yarns used in weaving are much finer than the yarns used in knitting, which provides the knitted fabric more bulk and less drape than woven fabrics and the precise control of several fabric parameters is difficult in knitting, which makes knitted fabric less suitable for airbag use.

3.2.4. Non-woven fabrics

In addition to the woven and knitted structures, there is also the use of non-woven structures for the airbags [154]. Non-woven fabrics are prepared directly from fibres bonded together by means of mechanical, chemical, heat or solvent treatments. Non-wovens are the class of fabrics which include materials such as felts, which are neither woven nor knitted. The production of thinner non-woven fabrics for airbags is rather difficult and non-woven fabrics typically lack strength unless densified or reinforced by a backing; so non-wovens are the least preferred material for airbag fabrics.

3.2.5. Finishing

Fabric finishing is an important step affecting the final fabric properties of airbags. If not controlled adequately, it can create variations in fabric properties across the length and width of the fabric and the airbags will not perform as required during their deployment. Compared with apparel fabrics, therefore, much more precision is needed in the processing of the airbag fabrics. An essential requirement is that the fabric has consistent air permeability, stretch and stiffness throughout. The finishing of airbag fabric may include desizing (for removal of size material), scouring and bleaching (to remove impurities and improve adhesion), heat setting (for fabric dimensional stability after processing) and coating (to provide controlled air permeability).

The number of fabric finishes applied to airbag fabrics is few compared to apparel fabrics. The process sequence for preparation of airbag fabrics is as follows:

Yarn packages → warping → sizing → weaving → greige inspection → scouring (and/or desizing) → heat setting → coating/laminating (optional) → calendering → final inspection.

There are two types of airbag fabrics available commercially: coated and uncoated [156–158]. Most driver side airbags are coated whereas the passenger side airbags are generally uncoated. This is related to the larger size of the passenger side-impact airbag, which develops a lower gas pressure on inflation and has longer inflation times compared to the driver side airbag. Finishing chemicals such as synthetic rubber (chloroprene,

Table 8. Difference between coated and uncoated fabrics [23].

Property	Coated	Uncoated
Air permeability	Precisely controlled	Variable
Packability	Bulky	Smaller package
Stiffness	Stiffer	Pliable to moderate
Pattern cutting	Easily cut	More difficult
Sewing	Easy to handle	More difficult
Burn thru	Good resistance	Poor
Deployment	Excellent control	Edge combing effects
Cost	High	Low
Recyclability	Difficult	Easy

polyurethane and chlorosulfonated olefin or silicone) and polychloroprene are used for the coating of airbag fabrics by methods such as knife coating, roller coating or reverse coating [159].

Cost plays an important role in airbag design. The coating of airbag fabrics increases their cost due to the additional cost of material and coating process itself. The overall coated cost of airbags can be reduced by (1) utilising a low-cost coating formulation, (2) using fewer coating steps and (3) applying very low coating add-on levels. In addition to the higher cost of the coated fabrics, the packing volume is at least 10% higher than the uncoated fabric. Hence, they need more space to be accommodated inside the steering wheel. In addition, the coated fabric needs a talc spraying to prevent the blocking/sticking of the coated layers when folded, which would otherwise cause considerable passenger discomfort during the airbag deployment. It is rather difficult to achieve a uniform coating due to the irregularities in a woven fabric surface, which can affect airbag performance.

Table 8 shows some differences between the coated and uncoated fabrics. On the one hand, the coating applied to the airbag fabrics increases the fabric-to-fabric and fabric-to-casing friction of the fabrics, which negatively affects the deployment response of the airbag. In addition, coated airbag fabric is very difficult to recycle, which adds to the cost for its disposal. On the other hand, the leakage of the hot gas through the seam can pose the risk of burns to the drivers or the passengers; hence, in the uncoated airbag fabric, the warp and weft threads should be closely packed to avoid the leakage of the hot gas through the pores.

3.2.5.1. Scouring. After the weaving is complete, the woven fabric for airbags contains residual size (if used for yarn preparation) applied before weaving. For example, a typical nylon fabric may contain about 10% polyacrylic size and 1.5% mineral oil, and a polyester fabric about 30% size and 1.5% mineral oil. However, for better serviceability, the amount of size left on the final airbag fabric should not exceed 0.35%. Hence, the woven airbag fabric must be treated with chemicals to remove the size once weaving is complete by the process of scouring and/or desizing [160].

In addition to removing the size material, scouring also removes the oil and stains on the fabric acquired during various processes. Yarns are generally lubricated during different stages of production to reduce the problem of static electricity and to improve efficiency in winding, warping and weaving. These lubricants are best scoured off before the fabric is run in the stenter where it might otherwise become fixed in the fabric. Scouring also removes the residual spin finish, helping to improve the adhesion of the coating with the fabrics. Generally, woven airbag fabrics are scoured in full width on continuous scouring ranges to prevent creasing.

Scouring also provides a number of other benefits such as the reduction of the phenomenon of fogging caused by the vaporising of oils in the fabric, which helps in relaxation of the material and develops bulk and texture. However, the scouring process has the potential to cause the fabric to shrink.

Special washing ingredients and high liquor turbulence are necessary for the removal of size. Woven nylon airbag fabric is impregnated with surfactants at pH 10 such as a non-ionic detergent [160]) and wetting agent [161] on a saturator to remove the residual size. The size on polyester fabric is removed by similar method to nylon or by dispersion, if the size cannot be dissolved in water. A high temperature is required for the removal of the mineral oil from the polyester fabric. During scouring, a high liquor ratio is used to avoid the re-deposition of the displaced size on the fabrics. The selection of appropriate agents for scouring is essential as any residue might react adversely with subsequent finishing treatments.

3.2.5.2. Heat setting

The temperature sensitive fibres in the airbag fabric may change their shape on heating, leading to shrinkage. Therefore, the airbag fabric is subjected to heat setting to achieve dimensional stability. After scouring, the fabric is dried and heat-set in open width in suitable machines such as stenter. The heat dries the fabric as it passes over the surface of a series of 4–12 steam-filled cans/rollers and retains its original dimensions.

This process of setting in the stenter provides dimensional stability, correct width and stretch to the fabrics [162]. These properties are controlled by the amount of overfeed, which is set after careful consideration of the processes the fabric will undergo after finishing. While processing lightweight airbag fabrics, the stenter must be equipped with appropriate devices for controlling the fabric's progress. For example, fabrics stentered with excessive overfeed may become slack in the width and fabric pulled out widthways will tend to lose length. For simple operation, clear instructions such as stentering to the correct width must be made, whether the stated width is between the pins (usable width) or overall width including or excluding the selvedge. Dimensional stability is essential for airbag fabrics as the airbag is subjected to extreme conditions and heat setting also removes undesired air pockets from the fabrics to ensure the fabric is tight. During the heat setting of nylon 6,6 fabric, the presence of moisture results in a higher degree of set because of greater mobility of the molecular chains [163], an indication that water or other solvents can be used with polyamide fibres to enhance the degree of heat setting. However, no appreciable difference is observed for polyester samples between the dry and wet heat-set conditions.

3.2.5.3. Coating/laminating. The coating process is carried out with silicone or other coating materials to achieve reduced air permeability and improved tensile and tear strength. Airbags are coated with one or more layers of polymeric materials mainly to enhance its performance (related to air permeability) and to a lesser extent to protect the fabric from detriment due to exposure to hot gases from the deployment mechanism. Some of the coatings also help to maintain a lower temperature of the airbag during its deployment, helping to prevent the occupants of the vehicle being burnt on contact with the newly deployed cushion.

Polychloroprene, which was used as a coating in the early stages of airbag production, is no longer used widely as it degrades when exposed to heat and releases hydrochloric acid which reduces the lifespan of the airbag [164]. In addition, polychloroprene-coated airbags do not meet the criteria of high abrasion and wear resistance [165]. These issues combined with the desire to decrease the folded size of the final airbag assembly by using less coating material has almost led to the universal replacement of polychloroprene with silicone-based materials (e.g. polydimethyl siloxane) for coating. However, the relative cost of silicone-based coatings is higher. Hence, very low coating add-ons are advantageous for silicone coating. The neoprene coating involves two to three steps, one vulcanisation step, one dusting step and one inspection step, whereas the silicone coating involves one coating step and one inspection step. In order to provide an alternative cost-effective and functional material to silicone, multi-layer coating systems have been developed. The polymers used for such coatings include polyurethane, acrylics and other similar materials used either alone or in combination with silicone.

In addition to the cost, the other problem associated with silicone coating is insufficient adhesion to the base fabrics during their extension at high temperature. This problem can be avoided by using a silicone rubber containing an organohydrogen polysiloxane with a specific epoxy group, which adheres tightly to polyester and polyamide fabrics [166]. The airbags now use synthetic rubber, especially polyurethane blends (such as polytetramethylene glycol or polyether; and polybutane adipates or polyhexane adipates) coated fabrics, as the coating is considered to be the most effective in terms of performance.

For example, US Patents 6,239,046 [152] and 6,641,686 [167] used two-layer coatings, where the layer contacting the fabric was polyurethane and the outer layer was an elastomeric polysiloxane. Some of the other multi-layer coatings include silicone cross linked with ethylene-containing copolymer [168] and polyurethane coating followed by a polymeric film (polyamide or polyolefin) [169]. The issue with multi-layer coatings is that the coatings may have compatibility issues, as a result of which it becomes hard to achieve the required uniform blend of the selected polymers leading to variations in the properties of the airbag fabric. The incompatibility problem can be overcome by using hybrid polymers or resins, which are the mixtures of two or more polymers forming an interpenetrating network (IPN) [170]. The IPN results from the interlocking of two resins with each other on a molecular level, thus providing superior properties (such as abrasion and toughness) compared to the simple blend without forming an IPN. The hybrid resins include resins with different physical or chemical properties. The hybrid polymers can be applied by methods such as knife coating, knife-over-roll coating, spray coating, impregnation coating, curtain coating, screen coating, reverse roll coating and transfer roll coating. They can also be used with one or more additives such as heat stabilisers, antioxidants, cross-linking agents, flame retardants, rheology modifiers, thickeners, anti-blocking agents, UV stabilisers, adhesion promoters, fillers and colourants. Some of the anti-blocking agents used can promote the flame retardant properties of the fabrics. In addition to these additives, synergists are used to enhance certain characteristics of the coating components. For example, some of the synergists, although do not exhibit the flame retardant property themselves, when used in small amounts, improve the flame retardancy of urethanes [145]. Once applied, the coatings are then dried in the temperature range 60–200 °C [170].

The hybrid resins provide better mechanical properties and ageing stability, improved abrasion resistance and higher resistance to edge combing of airbag fabrics than resin blends. The desired properties are achieved at lower add-on levels, thus a lighter weight and a lower-packing-volume airbag is achieved. The cost of a hybrid resin is cheaper than the cost of silicone coating systems. When considered as a whole, the hybrid blend typically exhibits properties that are a compromise of the bulk properties of the individual resins.

Several researches have been done on the use of hybrid resins for airbag fabrics. A hybrid resin composition was used for the coating of airbag fabrics, which imparted desired properties such as tensile strength and softness to the airbag [171]. The polymers used included urethanes blended with acrylates, vinyls and silicones, which formed an IPN. The hybrid resins were used alone or in combination with other single- or multi-component airbag coatings. Similarly, Keshavraj and Li [170] used the hybrid resins of urethanes blended with acrylates, vinyls and silicones as a solvent or an aqueous dispersion.

Recent airbag designs, especially side-impact airbags, need to hold the gas pressure longer under use. The use of lower levels of coating and the naturally lubricating silicone can lead to the shifting of yarns of the fabrics when put under stress. This can lead to the leakage of the inflating gas through the gaps formed by the yarn shifting and finally failure of the seam. Hence, the coatings should have effective air-retention properties and should restrict the yarns from shifting for the airbag to work properly. In some instances, a first layer of coating is applied for gas retention and a second protective layer is applied to prevent the airbag from sticking and to prevent the first layer from ageing and abrasion. For example, US Patents 6,177,365 [172] and 6,177,366 [173] used two distinct layers: the first layer (non-silicone) in contact with the airbag provided excellent adhesion and tensile strength, whereas the second layer (silicone) prevented the degradation of first layer. The two-layer systems provided excellent strength and edge combing resistance at relatively low cost.

Polychloroprene such as neoprene was selected as the first elastomeric coating for airbag fabrics for several reasons such as (1) neoprene-coated fabrics fulfilled the requirements for the airbag fabrics, (2) neoprene was environmentally and chemically stable, (3) the flame retardancy of neoprene is higher than the most competitive products and (4) it was readily available in the commercial market at low prices. By the end of 1980s, almost all the North American and European automobile manufacturers had adopted neoprene coatings for driver side airbag fabrics. On the other hand, most Japanese automakers were using silicone rather than neoprene due to the following reasons [28,165]:

(1) The performance of silicone-coated fabrics was superior as they have a high level of environmental stability and they retain their properties for longer, even at temperature extremes.
(2) Silicone polymers are chemically inert and do not adversely affect other materials with which they are in contact.
(3) They have low and constant air permeabilities even with fabrics with lower yarn densities.
(4) As the airbag restraint system was adopted late in Japan, they had no on-the-shelf system in which they had already invested. Therefore, they were free to adopt and choose from all available technologies.
(5) Compatibility with pyrotechnic as well as hybrid inflators where the silicone offers the fabric improved thermal protection against exposure to hot gas.
(6) The ability to be coated at low add-on weights (25 g/m^2) without the use of any solvent or change in the coating process. Hence, a decrease in the package size of the module is possible since silicone helps in the easy folding of the fabrics.

Table 9. The requirements of silicone-coated fabrics for airbags.

Property	Europe	Asia	USA
Usual silicone weight (g/m^2)	60–80	25–30	25–40
Flame resistance (FM VSS302, mm/min)	$<$100	$<$100	$<$100
Permeability (DIN 53887, L/dm^2/min)	$<$1	$<$1	$<$1
Abrasion resistance, in scrubs (NFG 37110)	$>$500	–	–
Abrasion resistance, in Wysenbeek (ASTMD 4157)	–	$>$50	$>$50
Tear strength (DIN 53356, N) for 420 denier	65–140	140–300	100–140
Usual blocking method	2–3 psi	–	2–5 psi

(7) Silicone-coated fabrics are more environmentally safe than neoprene-coated fabrics and can be recycled in the same way as the uncoated fabrics.
(8) The recycled silicone-coated airbags themselves can be processed like a first-quality airbags. The mechanical properties of recycled silicone-coated airbags are almost similar to the final properties of freshly coated fabrics.
(9) When the airbag coated with silicone is burnt, it produces gases such as water vapour and CO_2, unlike the hydrochloric acid, chlorine and other gases produced in the case of chloroprene.
(10) Silicone-coated fabrics exhibit good wear and abrasion resistance and good tear strength relative to softer neoprene coatings.

Until now, most of the domestic Japanese vehicle manufacturers have adopted silicone coating for their airbag fabrics. Silicone coatings do not compromise the long-term stability of nylon fibres, which ensures a longer service life of the airbag component. For example, it was shown that the silicone-coated airbag retained 91% of the initial strength, whereas it was 86% for a typical grade of neoprene. Similarly, the silicone-coated fabrics lost only 6 mg of weight compared to 27 mg lost by the neoprene-coated fabrics in the Taber abrasion test. Silicone coating is also used now in several parts of Europe, Asia and America. However, the coating requirements such as weight, abrasion resistance, tear strength and blocking test varies among these countries (see Table 9).

Table 10 shows the physical properties of a silicone rubber used in airbag coating [174]. It is a 100% solid, platinum-cured, low-viscosity liquid rubber and can be readily coated onto nylon fabric preferably with knife-coating equipment. The silicone coating is very cost effective as a low add-on level is used compared with neoprene. In addition, no solvent is incinerated or recycled as it is used as the 100% solid coating material.

The air permeability of an uncoated airbag fabric varies as shown in Figure 18. It can be observed that the air permeability of an uncoated airbag fabric varies across the width

Table 10. Properties of silicone for airbag coating [174].

Property	Value
Hardness, Shore A	39
Tensile strength, MPa (psi)	3.3 (475)
Elongation, %	200
Tear strength, N/mm (ppi)	5.2 (30)
Viscosity of uncoated rubber (100% solids)	60,000 cps

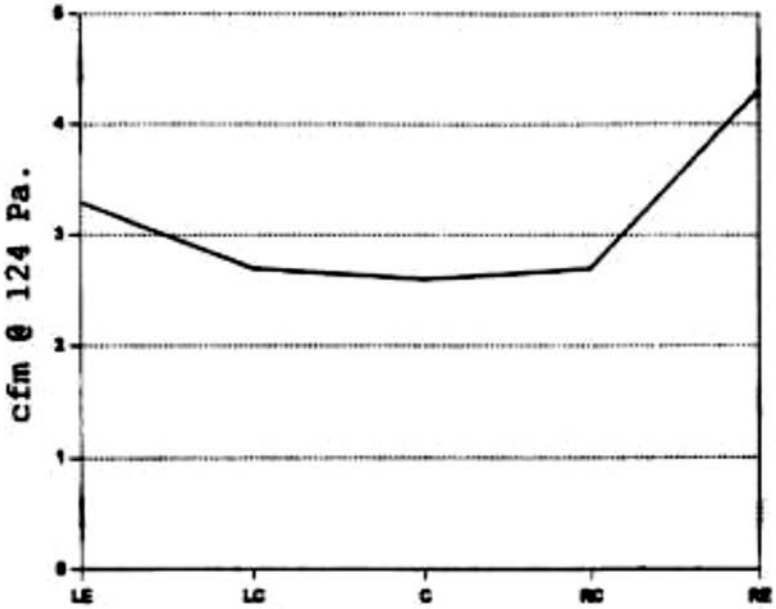


Figure 18. Variation of air permeability of a 630 denier (41 × 41) nylon airbag fabric. (LE: Left Extreme, LC: Left Center, C: Center, RC: Right Center and RE: Right Extreme)

for the same fabric construction. This deficiency must be eliminated or minimised in order to produce a more controlled deployment and reduce the cost. The air permeability can be controlled during various stages of the production such as weaving, finishing, coating, calendering or by impregnation and chemical grafting.

- **Weaving:** Increasing the thread density to achieve the maximum fabric packing can reduce the air permeability. However, there are limitations in the weaving machines' ability to pack the yarns very closely as quality issues will arise.
- **Finishing:** The airbag fabric is subjected to scouring (the process to remove contaminants) and heat setting (thermal treatment to prevent dimensional change). Hence, a fabric can be constructed with lower thread density, and if the scouring and heat setting can lead to thermal shrinkage, it can result in a lower permeability.
- **Coating:** The application of a coating (neoprene or silicone) on the fabric surface can result in zero or a near-zero air permeability on the fabric.
- **Calendering:** Calendering is a post-finishing treatment whereby the fabric is passed between two heavy rollers (bowls) under pressure and the fabric consolidates; calendering works well with the polyester fabrics. However, good results are not achieved with untreated nylon fabrics because of the shape-memory retaining properties of the yarn.
- **Impregnation/saturation:** The fabric is immersed into a bath containing a fabric finish such as coating or other chemical auxiliary material.
- **Chemical grafting:** This process can be used effectively to reduce the air permeability of various airbag materials. A controlled degree of air permeability can be

> achieved in this process by varying the yarn's linear density. The chemical grafting process makes the fabric surface hydrophobic, preventing moisture absorption. It can improve the seam strength in the airbag assembly and reduce or eliminate edge combing effects compared to uncoated and some silicone-coated fabrics. The grafted fabrics can be easily cut into multiple layers by die cutting, which reduces the high investment associated with laser cutting. Furthermore, the grafting process changes the surface chemistry to make it thermosetting compared to being a conventional thermoplastic throughout, which affords important protection during airbag deployment when its internal gas temperature is very high.

The processes described above in combinations are effective in producing a variety of substrates with improved permeability and fabric integrity.

Airbag safety systems rely on the permeable woven fabrics as their principal material of construction. The two major properties that affect the energy absorbing capabilities of the airbag fabrics are air permeability and biaxial stress–strain characteristics in the plane of the fabrics [144,175]. The permeability of the airbag fabrics affects the rate of inflation and subsequent rapid deflation following the deployment. The overall permeability can be better controlled by using different materials in different regions of the cushion. The use of multiple fabric panels helps in the development of complex three-dimensional geometries needed for a full-bodied cushion for the passengers.

The coating applied to airbags should combine the necessary gas-retention properties, flame retardancy, anti-blocking properties and stability to ageing. It is a challenge for manufacturers to achieve all these properties with a single coating layer, hence they use multi-layer or blended coatings. For example, a monolithic coating layer was applied to one surface of an airbag, which helped in gas retention, flame retardancy, anti-blocking and ageing stability [145]. The coating consisted of a blend of at least two different urethanes, one of which was inherently flame retardant and the other one gas-retaining urethane.

The two urethanes were synthesised, dispersed in water with surfactants, defoamers and other additives and adjusted to the desired molecular weight. These two dispersions were then combined in appropriate proportions by shear mixing, and applied by common coating methods such as knife coating, spray coating, impregnation coating, curtain coating and so on. The coating was dried at about 149 °C for 2 min to give an add-on of 20–34 g/m^2. As the coating was applied as a single monolithic layer, the process was simpler and cheaper, as it avoided the application of multiple coating layers and the separate process of applying anti-blocking agents. The performance of the airbag was equally as good as the standard, two-layer coated airbag. It was observed that the extreme conditions of temperature and humidity had very little impact on the air-retention and blocking properties.

3.2.5.4. Calendering. Calendering plays a vital role in controlling the air permeability of uncoated airbag fabrics [6]. It consolidates fibres in the yarn and the yarns in the fabric, increasing the fabric cover factor and decreasing its air permeability. Bloch [101] has designed an airbag fabric with polyamide yarn, which was pre-shrunk, heat-set and calendered at 130–160 °C, at a pressure of 30–50 torrs and a speed of 6–7 m/min. Fluorinated thermoplastic resins were applied during calendering for the purpose of sealing and providing additional heat resistance to the airbag fabric. In another approach, an uncoated polyester fabric was calendered at a pressure of 65–75 psi, a temperature of 177–188 °C and a nip of 1.27 cm to achieve the desired air permeability of 1 CFM [119]. The

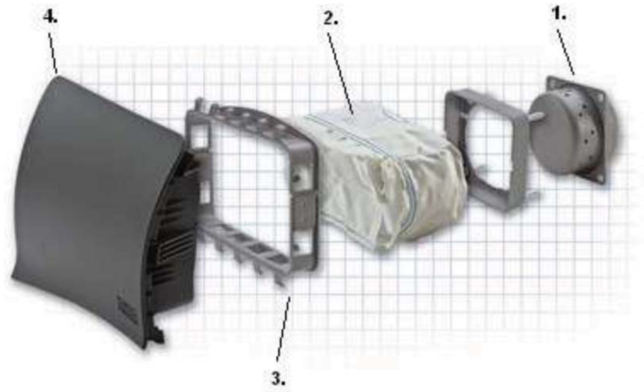


Figure 19. Major components of airbag module.

calendering process re-plasticises the thermoplastic yarn of the fabric and flattens the yarn to block the interstices. A polyester airbag fabric was also developed by Swoboda et al. [147], which fulfilled the airbag performance requirements without any coating or treatment such as heat setting and calendering. Hence, coating and calendering are not always necessary to achieve the desired properties.

3.2.6. Assembling

There are airbags of a variety of different shapes (such as spherical, oblong or even doughnut shaped) and sizes depending on specific vehicle requirements. Different airbag shapes provide different amounts and distributions of cushioning during a crash. Therefore, a significant part of the airbag studies should include investigating how well different shapes work. The driver side airbags generally consist of two circular panels of fabric joined together, whereas passenger side airbags are of different shapes, mainly made from two vertical panels and a main horizontal panel. There are four main parts in an airbag module as shown in Figure 19: (1) an inflator that produces sufficient gas to fully inflate the folded airbag; (2) a textile cushion or airbag; (3) a housing made of steel, plastic or even textile, which stores the folded airbag and the inflator and (4) a cover that opens as the cushion inflates.

Generally, the airbag panels are cut from the finished fabrics and sewn/joined together; the inflator components are assembled and the propellants are manufactured separately. Some of the automobile manufacturers buy the readymade components such as the sewn airbags, inflators and propellants, and then assemble them to make the complete airbag module. The amount of fabric needed for an airbag depends on the type and position of the airbag. The number of panels in the airbag cushion may vary from one to multiple. There are airbags with one (airbags without seam), two [176], three [177] and multiple panels joined together. The whole process sequence of airbag manufacturing starting from cutting to the final folding is discussed in the following section.

3.2.6.1. Cutting. The increase in the use of airbags in automobiles has led airbag manufacturers to determine the most cost-effective and flexible methods of cutting and sewing the airbags. Recently, the demand of consumers for more frequent model changes of the cars and hence the airbags, have necessitated flexibility in high quality cutting. Cutting systems which can meet all the above requirements are in high demand.

There are different cutting methods used for airbag fabrics. The major methods used for coated fabrics are mechanical (such as dies or reciprocating knife cutters) and for uncoated fabrics are based on the use of lasers [176–180]. In the former case, the fraying of the edges is prevented by the coating, and in the latter case the heat generated by laser seals the cut edges [181]. This is important as fraying can compromise the airbag's integrity during its deployment. Laser-based cutting systems are faster and more accurate than mechanical-based cutting systems.

The uncoated nylon airbag fabrics are best cut by laser-cutting systems. Although there have been trials to cut these fabrics with heated dies to prevent fraying, laser cutting is still preferred due to the following reasons:

- A good accuracy of $\pm$ 1 mm is achieved.
- The cut materials are free from fraying due to the sealing of the edges.
- The cutting dies are eliminated, which reduces the overhead cost for tooling.
- The elimination of dies gears the development of production plans.
- Laser eliminates the buffers between pieces.
- Laser cutting can be used for the coated materials when necessary.

The four major types of laser-cutting systems currently in use for airbag fabrics are (1) multi-ply static laser-cutting systems, (2) single-ply static laser-cutting systems, (3) multi-ply conveyorised laser-cutting systems and (4) single-ply conveyorised laser-cutting systems [182]. The multi-ply static laser-cutting systems were used in 1990s and their design was derived from those of the steel cutting machines. The productivity of these machines was more than 200 bags per hr. Several companies opted for these reliable systems as passenger side airbag volumes rapidly increased. In spite of the productivity advantages, these systems have the following disadvantages:

- Fixed-length cutting beds used for multi-ply static laser-cutting systems do not allow the optimisation of nest (pattern nesting) by length.
- Fixed-length cutting beds may result in end loss of 1 inch per ply per cut.
- Some fixed tables need spreading, cutting and unloading on the primary cutting surface, which decreases the system productivity.
- Often, a larger labour force is necessary to separate the cut components.

Investigation of the relationship between price, performance and operating cost showed that multi-ply static laser systems were not economical, which made them less attractive. Once the costs involved with cutting on the multi-ply static laser systems were established, manufacturers found potential in the use of single-ply static laser-cutting systems. The single-ply static laser-cutting system provides low cost, low maintenance and reduced labour costs; even so, the single-ply cutting system has the following disadvantages:

- Fixed-length cutting beds used for single-ply static laser-cutting systems do not allow the optimisation of nest by length.
- Fixed-length cutting beds may result in end loss of 1 inch per ply per cut.
- Most fixed tables need spreading, cutting and unloading on the primary cutting surface, which decreases the system productivity.

- Lower productivity ranging from 30 to 60 bags per hr.
- Large amounts of floor space needed due to the long length of tables.

Some companies also installed the multi-ply conveyorised laser-cutting systems, which provide the following advantages:

- High productivity ranging from 280 to 350 bags per hr.
- Reduced end loss due to continuous cutting from rolls or spreads of 10 m or more in length.
- Reduced labour cost as the total number of plies ranges from three to six making separation of cut parts easier.
- Reduced floor space requirement.

Despite the fact that multi-ply conveyorised systems can produce high volumes of airbags with reduced labour, there are still some major disadvantages such as:

- Paper separators are still needed to prevent fusing of intermediate fabric layers.
- End loss is not eliminated as spreads are generally needed because the fabric dynamics prevents multi-ply cutting from rolls.

Several manufacturers have started installing the single-ply conveyorised laser-cutting systems, which can cut single ply continuously from the rolls. The advantages of this system are as follows:

- The productivity ranges from 65 to 100 bags per hr, resulting in an excellent cost–performance ratio.
- End loss is very low due to cutting from rolls with long nests butted together.
- These systems are about 70% cheaper than the multi-ply conveyorised systems.
- The floor space requirement is very low.
- Reduced labour cost since there are no parts to separate.
- These systems are flexible for fabric changeovers.

Some of the leading manufacturers of laser cutter devices for airbag fabric include Lectra Systems and Gerber Technology. The cutters are integrated with computers and can precisely cut the patterns as designed in the computer software. One of the laser-cutting systems, Vector (from Lectra), is said to provide enhanced productivity and considerable material savings [183]. These cutters enable manufacturers to simultaneously cut several layers of airbag fabric and benefit from an unloading assistance system.

One-piece woven (OPW) airbag cutters are also available from both the companies. Specialised technology for the cutting of OPW airbags, manages the weaving flaws while maintaining the geometry and the dimensions of the shapes of the pieces. Prior to cutting, necessary information on the fabric can be communicated to the software, to achieve a level of precision in compliance with the automotive industry's safety standards. Scanners attached to the cutters verify and automatically adjust the cutting path depending on the actual deformation of the material, resulting in high-quality cut pieces. The laser-cutting system, Keehwa (from Gerber Technology), can cut airbag fabrics for both OPW and open-weave material (OWM) in multiple layers [184].

In addition to the above laser-cutting systems, the other methods widely used include die cutting and reciprocating knife cutting. There have been several developments in knife cutting, which made these systems a viable alternative over die cutting. The advantages of knife cutting over die cutting include the following:

- Elimination of dies reduces tooling cost.
- Knife cutters provide more flexibility and faster product development cycles.
- Knife cutting needs smaller buffers compared with die cutting, which saves large quantities of material.
- Knife cutters can cut longer nests than die-cutting systems and reduce end loss.
- Most knife cutters now offer an accuracy of $\pm$ 1 mm on contours and internal holes.

These developments have led the airbag manufacturers to adopt knife cutting as an alternative to die cutting. Recently, Lectra Systems offered its Vector 7000 knife-cutting system for airbags, which can achieve (1) cutting of spreads from 15 to 30 plies, (2) average perimeter speed of 7 m/min on 30 plies and (3) cutting of spreads of 10 m length or higher depending on the spreading tables used.

The airbag panels can also be cut on a mechanical topspin or pizza cutter, which can be controllably moved along *x* and *y* coordinates [185]. The name “Pizza cutter” is given as it cuts circular panels. This cutter, generally used for driver and passenger airbags, uses the edge of a disc to cut broad arcs and circles. The topspin cutters cannot, however, cut the much tighter and smaller arcs of the laser cutters.

The airbags in automobiles are prepared in different shapes such as circular [177], spherical and oblong. Manufacturers have always focused on reducing the airbag’s cost by using the fabric more efficiently, reducing the amount of fabrics to be cut and reducing the amount of fabric used per bag (for lower packing volume), which reduces the shipping weight. However, there is a limit below which the airbag volume cannot be reduced as the performance of the airbag would be affected.

While cutting the panels from the airbag fabrics, it is necessary to cut the maximum number of panels from a fixed area through close-packed nesting of the panels. Minimising the number of different geometries of the panels and using geometries with substantially straight-line profiles permits an enhanced number of panels to be cut from a given fabric. In addition, the use of panels with straight-line profiles permits the panels to be attached to each other using straight seams. The straight seam configuration provides a cost-effective method of producing the airbags. The passenger side airbags need a greater amount of fabric, which then needs longer seams to attach fabric panels.

The driver side airbags are circular in shape, formed by joining/sewing two similar circular panels face to face. During their deployment, circular airbags are subjected to substantial tensile stress that can cause seam failure. To avoid this problem, polygon-shaped (hexagon and octagon) airbags were designed by Keshavaraj [186],

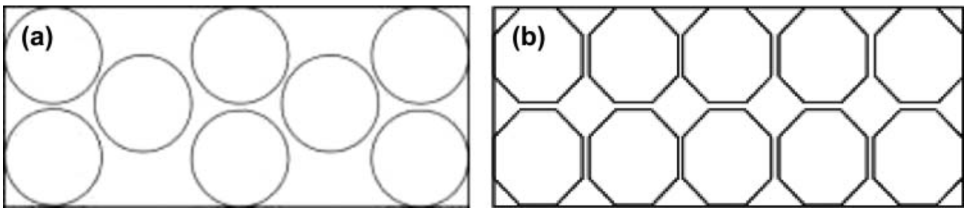


Figure 20. Fabric utilisation for (a) circular panels and (b) polygon-shaped panels.

which were joined adhesively by chemical, thermal or other means. The panels of the airbags were made with the same polygon shape, but in different sizes. One panel was larger than the other and the extrapolating edges of the larger panel were folded into the smaller panel. Joining the lapped panel adhesively produced a wide seam area with a relatively continuous area of attachment over which the stresses of inflation are manifested as shear forces, thus avoiding the chances of seam rupture or leakage. In addition, fabric utilisation in the case of polygon shapes (with at least five sides) is better than for circular panels (Figure 20).

Keshavraj [171] also developed an airbag with very low amounts of fabric comprising substantially straight seams. The airbag was easy to assemble with minimum labour and yielded the maximum amount of available inflation airspace volume. The effective fabric usage factor for the airbag was less than 0.033. The effective fabric usage factor is derived from the effective fabric usage index, which is the quotient of the total amount of fabric utilised to make the airbag cushion over the total volume of available inflation airspace within the airbag cushion. The airbag used fabrics more efficiently with less waste in terms of unused fabric.

3.2.6.2. Joining of panels. After the panels are cut into shape, they are joined together by appropriate methods. The methods of joining the panels involves sewing [187,188], welding [189,190], joining by adhesives [191], weaving the panels together in a loom and other processes. For the reasons of safety, and therefore achieving proper seam strength and stability, airbags are mostly joined by sewing. The sewing machine needs to be able to stitch the airbag panels without damaging the airbag fabric or the sewing thread. This can be achieved by suitable selection of sewing machine, sewing threads and proper adjustment of sewing parameters such as needle type, stitch length, stitches per min and machine speed. In the case of a car crash, an incorrect stitch length or skipped seam in an airbag could prove fatal to the occupants.

Sewing thread is an engineered material, which holds all the cut panels together [192]. It joins the fabric components by forming a seam that is intended to provide uniform stress transfer from one fabric piece to the other, thus preserving the overall integrity of the assembly [193]. The sewing threads are smooth, hard-twisted multi-ply yarns, treated with special finishes to make them resistant to stresses in their passage through the needle eye, the airbag fabric itself and other parts of the machine involved in seaming and stitching operations.

Sewing threads used for airbags are required to maintain their performance throughout the life cycle of the airbag. The sewing threads used for airbag fabrics should have high heat resistance, strength and elasticity [194]. These requirements are mostly satisfied with the sewing threads of polyamide fibres, which have greater specific heat capacity, melting point and heat of fusion than sewing threads of other fibres such as polyester. In addition, polyamide fibre has the high strength-to-fineness ratio and high extensibility compared to polyester fibres. Its higher elasticity helps to accommodate the stress and distribute it uniformly along the circumference, when airbag is deployed.

Problems that have to be overcome even for polyamide and polyester sewing threads are fusing (due to needle heating) and seam puckering (the elasticity is a contributing cause) [193], hence, the application of various chemical finishes overcomes these issues. In addition to polyamide and polyester, aramid (Kevlar®) sewing threads are also used for sewing airbags and the stitch densities are selected carefully for maximum performance.

Although the most widely adopted joining process for airbags is sewing, there are a growing number of other processes such as welding [181], moulding and fusing. In welding, two fabrics are joined using a thermoplastic material with the application of heat. There are four ways of applying the heat such as radio frequency welding, hot air welding, ultrasonic welding and hot wedge welding. An important requirement for welding is the presence of a thermoplastic material, which may either be the fabric itself or an additional material sandwiched between the textile layers to be welded. In this process, the thermoplastic material is melted, penetrates the fabric layers pressed into close contact with it and upon cooling, secures the bond.

In addition to the above four methods, laser welding [181] can also be used for joining materials. However, laser welding processes for technical textiles are rarely described in the literature. Some describe a laser sewing machine in which the textile layers are fed and at the same time pressed together by rolls. Using a CO_2 laser beam of wavelength 10.6 μm, the laser radiation interacts with the interface region directly in front of the rolls. The corresponding laser seams have qualitatively good external appearance, as they are clean and the welding fume is minimal.

Welding provides better and more easily produced attachment points between multiple fabric layers, with reduced air and gas permeability compared with sewing. The strength of the bond can be altered by using different polymeric materials and changing the thickness of these materials. However, the welding method has certain limitations such as:

- A welded seam works well if the fabrics are joined with a lapped seam. However, this seam creates the problem of raw edges [195].
- The welded seam is less flexible resulting in lower extensibility and recovery than sewn seams, which can result in seam breakdown.
- An incorrectly joined welded seam is impossible to alter, whereas the sewn seam in most cases can be undone and re-sewn.

In some designs the combination of welded and sewn seam can be used to improve the performance of the airbags. For example, an inflatable airbag was developed by utilising welding and reinforced with sewn seams to join two fabrics together [196]. Sewn seams were used adjacent to the welded areas, which provided stronger reinforcement and thus more reliable non-permeable fabrics. Coatings were placed over the sewn seams at the joining points in order to seal the potentially loose portions of such seams and/or to keep the individual yarns of the airbag fabrics at the attachment points stationary. This would prevent yarn shifting and openings being generated for gas or air leakage. The coatings are not, however, fully capable of providing the needed benefits due to:

- Most coatings are composed of silicones, which lubricate the yarn and aid yarn shifting.
- High thickness of the coating is needed which can create tackiness between fabric layers in the airbag during storage in its inflation module.
- During the storage of the coated airbags in a small volume, the coatings may cause increased incidence of adhesion between the contacting fabric layers, consequently, creating difficulties in unfolding the airbag upon inflation.
- The coatings are relatively costly.

The main aim in airbag manufacture is to produce highly effective airbags at reduced cost. The above-mentioned drawbacks can be overcome with the use of advanced techniques of welding and sewing. In addition, advancements in fabric manufacturing and automation in production line have helped to achieve airbags with improved performance.

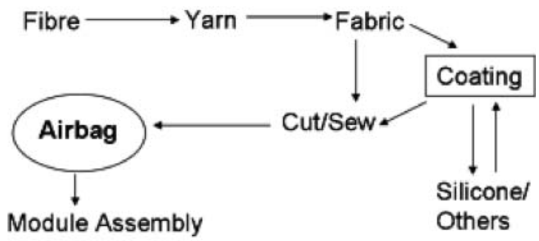


Figure 21. Process sequence for the manufacturing of airbag module assembly.

The sequence of operations for manufacturing of airbag fabrics and the subsequent module is given in the flow chart in Figure 21.

Some of the airbag designs use dual airbags. In dual airbags, the main outer airbag contains an inner smaller airbag with holes. During deployment, the gas is filled in the inner airbag first, which then leaks into the main outer airbag through the holes. Hence, the dual airbag can reduce the speed of deployment and reduce the possibility of injuries caused to occupants compared to the single airbags.

Several airbags include straps called tethers inside the fabric to prevent the airbag from reaching too close towards a driver or passenger and violently slamming them in the face [197,198]. The tethers are optional and some manufacturers do not install them in their airbag designs. Although a company can save by not using tethers, untethered airbags cause significant injuries such as blindness and other eye injuries, facial abrasions and other traumatic injuries to the occupants, and the use of tethers can reduce/prevent many of these injuries. In addition, tethers help in proper positioning of the airbag during the deployment and help in achieving a more consistent airbag deployment, which reduces the effect of manufacturing inconsistencies.

Bloch [101] used rubberised stretchable polyamide straps to absorb the energy during deployment. When the pressure in the airbag is released, these straps return the airbag to its original form and size by means of reversible extension of the straps.

Most of the manufacturers do not provide any information to consumers about whether tethers are used in the airbags in their cars, which prevents consumer awareness about the series of events during the airbag deployment.

3.2.6.3. Folding. After sewing is complete, the airbag has to be packed in its cover with extreme care to ensure smooth deployment without one part of the bag getting in the way of the rest. The importance of airbag folding is equivalent to that of parachute folding. The airbags are packed in the vehicle together with the inflators, in many designs as a part of the airbag module [199]. In the airbag module, the airbags are usually arranged in a folded state in such a way that it can unfold as quickly as possible in a specific direction.

Different airbags are folded with different numbers and types of fold by numerous methods. A number of folds such as simple fold, open fold, rolling fold, tuck fold, accordion fold, reversed accordion fold, pleated accordion fold, Leporello fold (L-fold), raff fold, stochastic fold, ring fold and overlapped fold can be selected for this purpose [200]. Of these, four folds predominate commercially: L-folding, ring folding, accordion folding and stochastic folding [201].

L-folding: L-folding is quite simple to achieve and was used in early airbag designs. The airbag is folded by hand to generate a compact airbag packet and lumped together from the side. In this fold, the individual folding lines continue in a linear direction, which can cause a self-blockage of the airbag during deployment; hence deployment results in a higher stored energy level due to the significant rise of the pressure from the successive phases in opening. The occupant receives a "punch-out" effect due to the higher force of deployment.

Ring (R) folding. In this folding, the airbag fabric is arranged circularly around the propellant. The main folding lines form concentric rings around the gas propellant and proceed along closed lines. Hence, during airbag deployment, the gas can flow into the airbag without any hindrance and without any self-blockage. The final form of the airbag is achieved earlier than in L-folding; also, the punch-out effect during deployment is reduced, as the whole airbag cushion is not catapulted against the occupant, but instead it is deployed first to the side and then subsequently onto the occupant.

Accordion (Z) folding. The airbag fabric is folded similar to an accordion in a radial circular manner around the propellant. The folding lines also proceed along closed lines around the gas generator similar to those of ring folding. The airbag does not experience a self-blockage and deploys more to the side rather than straight, and without the "punch-out" effect of L-folding.

Stochastic (S) folding. This fold does not follow any rule and is rather chaotic. In the fabric, the folding lines are arbitrarily arranged. The direction of airbag deployment depends on the way it is folded into the airbag case.

Conventionally, airbags are folded at predetermined points by spreading out the airbag cushion flat on a working table then folding manually or by conventional folding systems or both. Conventional folding systems have certain disadvantages such as requirement of large amount of space for folding and a folding process which is time consuming. Hence, there are always requirements for complicated automatic folding systems adapted to different airbag shapes. To cater for this requirement, different advanced designs such as a plunger mechanism [202] and other folding devices [203–206] have been proposed to overcome the difficulties associated with the conventional methods of folding.

Jang et al. [207] developed systems and methods for folding the airbags. The system consisted of a cavity having a rear wall and a top wall, which assisted in the folding of the airbags. Several other folding devices are described in various US patents [208–211] and other patent [212].

During the folding of the airbag, the fabric of the folded airbag rises from the folded state due to the following reasons: (1) the airbag fabric has no previous fold habit and (2) the tendency of the fabric to return to its unfolded state. To avoid these effects, the folded airbag can be held by a band made of film, which breaks during airbag deployment by means of the deployment pressure [213,214].

The folding should allow the tethers joined to the airbag to control its protrusion into the car during deployment. A cover can be fitted over the bag to protect it from abrasion. Airbags are rigidly secured with some solid parts or retainers inside the housing so as to prevent the free flight of the airbag cushion during the deployment.

The commercial folding machines are not flexible enough to allow different types of airbag folding. A new machine design is required for each new folding style. Hence, several manufacturers are trying to design an adaptable machine that can accommodate a variety of folding tools, so that a single machine is capable of folding a wide range of airbags.

The folding devices fold the airbags into different profiles depending on the location of the airbags (driver side, passenger side or side-impact airbags), structure of the vehicle and arrangement of the airbag and inflator. The quality of folding and the production efficiency during folding can be increased by automatic folding devices with a programmable logic controller and sensors.

The selection of the best and the most reliable way of folding for smooth deployment of an airbag still needs further research with the help of modelling techniques. Several simulation studies have indicated that the folding pattern of airbags has a significant influence on the injury risk of OOP occupants. L-folds generate a higher risk of injuries [215]. It was observed that with L-folding, the injury potential was higher due to the high opening pressure compared to the other foldings, "R, S and Z". Hence, simulation studies should be conducted to further investigate the unfolding behaviour of the different types of folding and the influence of the folding pattern on the risk of injury to occupants. The finite element (FE) analysis is not applicable for modelling of different airbag folding types.

Storing chambers for airbags may be of no specific shape or of particular shapes such as spherical [176], cylindrical and tubular. The spherical chamber is preferred over cylindrical or tubular chambers as it has the smallest surface for the same volume. The airbag is folded into a small volume while packed in the chamber and connected to the inflator and sensors.

The exit opening of an airbag is covered by appropriate means such as a cover cap [216]. The covers are mounted on the steering wheel, dashboard, door, roof of the vehicle and other locations, which are opened from a closed position to a clearing position permitting the emergence of the airbag under internal gas pressure. In some instances, predetermined yield lines are provided in order to enlarge the opening as a large opening diameter, which is required for airbag deployment [216].

In order to simulate the behaviour of an airbag, modelling in the initial folded position inside the chamber is required. Airbag simulation studies consider the airbag folded into a small chamber and tucked into the (simulated) steering wheel or dashboard. Hence, the simulation of an inflated airbag should always start with the simulation of a folded airbag. The simulation of the airbag during the deployment and subsequent venting and flattening in real crash conditions is rather difficult. The simulation studies on airbag deployment should consider the type of fold, volume of airbag, type of cover and angle of deployment. The deflation of an airbag is simulated by considering the airbag as a rigid object, then locating the creases that flatten it, followed by folding it up into a small packet.

The static unfolding test and the shot energy test are used for the airbag model validation. In the static unfolding test, the airbag is ignited and unfolded into the air. The unfolding process is filmed with a high-speed camera and the internal pressure in the airbag is measured. In the shot energy test, a hemispherical hanging impactor simulating the shape of the head is hit by an unfolding airbag and then accelerated upwards. The injury potential of the airbag is measured from the amount of shot energy transferred from the airbag to the impactor. This test is simulated by varying the distance between the airbag module and the impactor. The injury potential of the airbag is interpreted in terms of the effect of "punch out", "bag slap" and "membrane loading". During the initial airbag deployment phase, these effects are stronger and the injury potential of the airbag is higher.

3.3. Testing of airbags

Testing is carried out to prevent substandard products progressing further in the production cycle or to improve the finished product quality. Hence, various quality parameters are tested for the airbag fabrics and the other components of an airbag module before they are finally assembled. The important performance requirements of airbag fabrics are breaking strength and elongation, energy absorption, heat resistance [217], air permeability [143,148] and resistance to ageing [165]. In addition, the other components are also tested for their quality and performance. All such tests can be performed by standard procedures such as ASTM, ISO or other international or local standards.

3.3.1. Testing of fabrics

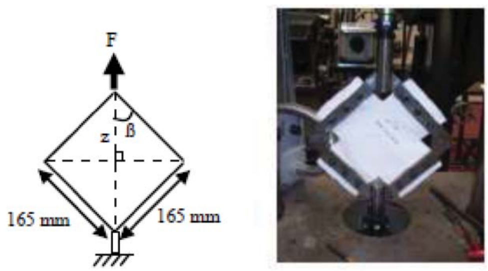
Some of the car companies manufacture the airbag fabric in-house; others receive the woven airbag fabric from vendors. For satisfactory deployment, the airbag fabrics should meet certain performance requirements such as:

- High tensile and tear strength.
- Low air permeability (to retain the gas during its deployment).
- High bursting strength (to withstand high pressure during inflation).
- High flexibility (to reduce the shock to the occupant).
- Low stiffness or good packability (so that it can be folded in a small possible volume).
- High heat resistance (to prevent the damage and rupture of the fabric during deployment).
- High resistance to seam failure or edge combing (to prevent gas leakage through the seam).

The properties of the base fabric such as type and linear density of the yarns, thread density, weave, areal density, breaking force and elongation, tearing strength, bursting strength and air permeability affect the functional properties of an airbag [142,218,219]. The fabric is inspected for all the above listed properties and material defects following various standard test procedures. A stringent quality control system is needed for achieving airbags with zero defects.

In addition to the above tests, uniaxial [220,221] and biaxial tensile tests [158,222] are also done to assure the fabric performance. Uniaxial tensile tests are performed in constant rate of elongation (CRE) machines to evaluate the tensile strength and elongation of airbag fabrics primarily in the weft direction. Sample sizes of 100 mm (or 200 mm) × 50 mm are used with the tests conducted at 100 mm/min (static load) and 1 m/sec (dynamic load) [223].

Biaxial tests (referred to as picture frame tests) are used to investigate the shear stiffness of airbag fabrics, which is a function of shear stress against shear strain [224]. The picture frame is a frame jointed by pins clamped around the airbag fabrics, fixed at the bottom corner and loaded at the top corner (Figure 22). The airbag fabric is clamped in



(a) (b)

Figure 22. Biaxial tests of airbag fabrics: (a) schematic diagram and (b) the sample in test.

the frame with the warp and weft threads running parallel to the sides of the frame. Hence, the displacement of the top corner of the frame applies a shear force to the fabric. This test can be used for better prediction of the behaviour of the fabric during deployment compared to the uniaxial test.

During their lifespan, airbags face extremes of hot and cold. The airbag should retain all its essential properties during its life cycle. Hence, for a smooth and accurate deployment, evaluation of the ageing characteristics of the airbag fabric is essential. The amide linkage (–CO–NH–) of nylon 6,6 is susceptible to ultraviolet (UV) degradation [225], which can affect the airbag performance. Hence, the airbag fabric should be treated with appropriate finishes to prevent the UV degradation.

The air permeability of the airbag fabrics is an important parameter in determining the rate of inflation and subsequent deflation during an impact. Generally, low air permeability is absolutely necessary for the airbag fabrics especially in the case of uncoated fabrics, for them to deploy promptly to cushion the occupant. High air permeability will release higher amount of the gas too rapidly and when the occupant strikes the airbag, it may not provide sufficient resistance to prevent the occupant from hitting the hard parts of the car. On the other hand, if the permeability is too low, there will be release of too little gas through the fabric during deployment and on an impact, when the occupant strikes the airbag, the cushioning effect could be too hard, causing rebound of the occupant and increasing the likelihood of "whiplash injuries" [226,227]. For these reasons, the air permeability of the airbag fabric requires close control, not least, because uncoated airbag fabrics are replacing the coated fabrics, and high permeability can cause facial burns to the occupant due to excess leakage of hot gas through the fabrics during airbag deployment [228].

The standard static permeability methods adopted for the evaluation of air permeability of apparel fabrics, which work under relatively low pressure, are not suitable for airbag fabrics which work at high pressure. Technical textiles such as automotive airbags, landing airbags and parachute fabrics are subjected to high initial pressure (e.g. 200 kPa for airbag fabrics) which is then required to subside as the airbag becomes fully deployed. Hence, dynamic permeability is the preferred method of test for these fabrics rather than static permeability. Static permeability is the ability to transmit permeating fluid at a constant pressure drop, whereas dynamic permeability relates to the mass transport under transient pressure conditions. Dynamic permeability is performed under a high initial pressure, where the nonlinearity between the pressure and velocity cannot be ignored. Dynamic air permeability for airbag fabrics has been measured by several techniques such as the blister inflation technique [217,229,230], the shock tube experiment [143] and other techniques [231,232].

During airbag deployment, the high initial pressure can result in high deformation of the fabric structure, leading to a change in its air permeability. Hence, the dynamic air permeability is measured under transient pressure conditions; dynamic air permeability is an intrinsic property determined by the change of fabric geometry and structure due to high pressure. The effect on fibre and yarn arrangement, yarn porosity and fabric thickness is determined alongside pressure-induced deformation when measuring the dynamic air permeability. The number of fabric layers and initial pressure drop affect the level of deformation during the test.

Xiao et al. [233] investigated the dynamic air permeability of woven fabrics. It was found that the dynamic air permeability of loose fabrics was higher than the static air permeability, while it was lower for tight fabrics. The difference between the static and dynamic permeabilities of tight fabrics could be reduced by using more fabric layers and lower initial pressure.

Keshavraj et al. [144,219] developed a quasi-steady-state blister inflation technique in which a fabric blister is created by a pressure drop across the fabric and is maintained while data on the permeability are recorded. The blister inflation technique was used to measure and compare the performance of nylon airbag fabrics with polyester fabrics. It was observed that a reduction in temperature to below room temperature resulted in an increase in permeability due to fibre contraction at the lower temperature. The reverse phenomenon occurred from the expansion/swelling caused by the increase in the temperature above nylon's glass transition temperature (T_g). In the case of polyester fabrics, calendering caused permanent flattening of the fibres and hence an increase in the fabric cover factor resulted in lowering the air permeability.

Narayanan [138] investigated the dynamic air permeability of airbag fabrics using the blister inflation technique. A blister was formed in the fabric (held between two metal plates as a flat sheet), when the air was allowed to pass through the fabrics. The air tank pressure and the height of the blister were measured by transducers. It was observed that a higher initial pressure led to an increase in the permeability. It was also observed that a tight fabric was less sensitive to the initial pressure change than a loose fabric.

A permeability tester was also developed for measuring gas velocity through the airbag fabrics over a pressure change from 40 to 60 kPa [234]. A high-speed valve was used to release gas from a top chamber into a bottom chamber and then across the fabrics from which the air permeability was measured. In addition, Partridge and Mukhopadhyay [143,157,232] investigated the permeability of a series of airbag fabrics by using a commercial dynamic permeability tester (FX3350 Textest AG). The dynamic tester was a table-mounted instrument, which can produce a pressure load up to 200 kPa above the atmospheric pressure. A high-speed valve was used to transport the gas through the test sample, and the gas pressure and velocity were reported by transducers.

In another approach, the air permeability of airbag fabrics was evaluated by measuring the velocity of the reflected shock wave [148]. Shock tube experiments imitate airbag inflation and are performed by fixing an airbag fabric sample near the end of an open driven section. The airbag fabric is reflected, when a plane shock wave impinges it. An increase in the pressure at front face of the airbag fabric leads to the airflow through the permeable airbag fabric. The air permeability of the airbag is measured by measuring the velocity of the reflected shock wave. It was observed that at relatively high pressure, the dynamic permeability from the shock tube experiments was lower than the static permeability from the conventional permeability testing method. This phenomenon was attributed to different influences of the steady pressurisation on the airbag fabrics in static experiments and instantaneous pressurisation in the shock tube experiments.

The static permeability tester consisted of a pipe with one end covered by the airbag fabric and the other end connected to a storage tank of a large compressor via a mass flowmeter for measuring flow rates. An electrostatic capacitance type pressure gauge mounted at the upstream side of the airbag sample was used for pressure measurement. In both the experiments (dynamic and static) air was used as the driver gas. The experiments were performed at atmospheric temperature of 22 °C and the equipment pressure difference was 100 kPa. The list of important test methods followed for airbag fabrics are listed in Table 11.

Table 11. Summary of major test methods used for airbag fabrics [102,142,235].

Parameter	Standard	Test name/description
Air permeability (static)	ASTM D 737–96, DIN 53887	Air permeability is the rate of airflow passing perpendicularly through a known area under a prescribed air pressure differential, between the two surfaces of the fabric.
Air permeability (dynamic)	ASTM D 6476	Standard test method for determining dynamic air permeability of inflatable restraint fabrics.
Bursting strength (diaphragm method)	ASTM D 3786–01	Bursting strength is the distending force, applied at right angles to the plane of the fabric, under specified conditions, which will result in the rupture of the fabric.
Breaking strength and elongation	ASTM D 5034	Breaking strength is the force a material can withstand before it fails.
Tear strength	ASTM D 2261, DIN 53839	Tear strength is the capacity of the fabric to withstand the tearing force required to propagate a tear after its initiation.
Abrasion resistance	ASTM D 5446, DIN 53528	The ability of a material to resist wear caused by rubbing, scraping or erosion, which tends progressively to remove material from its surface due to friction.
Fogging resistance	DIN 75201	The standard specifies the determination of the fogging characteristics of trim materials used in the passenger compartment of automobiles.
Flammability	FMVSS 302, DIN 75200	It describes how easily a material will burn or ignite, causing a fire or combustion.
Performance of airbag	ASTM D 5428–93A	Standard practice for evaluating the performance of inflatable restraint modules.
Specific packability	ASTM D 6478	Specific packability of the airbag fabric is the volume occupied by the fabric at a specific load in a specific cell.
Edge comb resistance	ASTM D 6479–02	Edge comb resistance indicates the relative tendency of a fabric to pull apart under seam stress or similar action.
Terminologies	SAE J1538	Glossary of automotive inflatable restraint systems.
Identification	SAE J1856	Identification of automotive airbags (at vehicle disposal).
Physical properties	ASTM D5446–94	Determination of physical properties of fabrics.
Ageing	ASTM D5427–93A	Standard practice for accelerated ageing of inflatable restraint fabrics.
Visual inspection	ASTM D5426–93	Standard practices for visual inspection and grading of fabrics used for inflatable restraints.
Blocking test	SAE J912	Determination of blocking resistance of automotive trim materials. This determines the degree of surface tackiness, colour transfer and loss of embossment when two materials are face to face.

(*continued*)

Table 11. (*Continued*).

Parameter	Standard	Test name/description
Bow and skewness	ASTM D 3882	Standard test method for bow and skew in woven and knitted fabrics.
Count of woven fabric	ASTM D 3775	Standard test method for warp (end) and filling (pick) count of woven fabrics.
Mass per unit area	ASTM D 3776	Standard test methods for mass per unit area (weight) of fabrics.
Thickness	ASTM D 1777	Standard test method for thickness of textile materials.
Coating adhesion	ASTM D 4851	Standard test methods for coated and laminated fabrics for architectural use.
Odour	SAE J1351	Hot odour test for insulation materials.
pH	AATCC-81	pH of the water extract from wet processed textiles.
Stiffness	ASTM D 4032	Standard test method for stiffness of fabric by the circular bend procedure.
Warp residual sizing	ASTM D 6613	Standard practice for determining the presence of sizing in nylon or polyester fabrics.
Sewing threads	ASTM D 204	This test method is used for the measurement of sewing thread physical properties.

In addition to the air permeability test, the other essential test for airbag fabric is the edge or seam comb resistance test. It is the relative tendency of a fabric to pull apart under seam stress or similar action, which is very essential to maintain airbag's integrity during deployment. In this test, one end of a test specimen is clamped within one jaw of a CRE tensile testing machine and a special fixture with a row of equally spaced needles pierces holes through the opposite end of the specimen. A tensile force is applied (as per ASTM D5035) to the specimen until it ruptures. The force required to rupture the fabric is the edge comb resistance of the fabric [236].

The resistance to seam combing of airbag fabrics is an essential parameter affecting the performance. Seam combing or yarn shifting is the relative tendency of a fabric to pull apart under stress at the seams, due to inflation. This is a significant problem for airbag fabrics after prolonged storage at extreme conditions (-40 and 50 °C) [168]. When a sewn seam is put under stress, the naturally lubricating coating may allow the yarns to shift. This shifting can lead to the leakage of the gas during the deployment of the airbag. However, for the effective performance of an airbag, the structural integrity of the seams at attachment points is essential. Hence, coatings are applied over the sewn seam to restrict the yarn shifting in the airbags. The coating selected should be economical, effective at lower add-on levels, should provide low air permeability, resistance to yarn shifting and resistance to ageing over long period of storage.

A polyester fabric was developed with improved resistance to edge combing [134] (edge comb resistance $>$ 350 N at 20 °C). The fabric was coated with an acrylic polymer/copolymer finish with 1–4% add-on level. The uncoated fabrics started to fray during sewing and exhibited edge combing.

The edge combing resistance of uncoated nylon fabrics is superior to polyester fabrics. Hence, the coating of polyester is necessary to improve the edge combing resistance. Although uncoated airbags have attracted attention, they become frayed during sewing and exhibit seam combing. The progressive improvement of inflators has helped to enhance the inflation speed of airbags dramatically; hence, the airbag fabrics now need to have higher energy absorbability to prevent passengers from exposure to the excessive impact during inflation.

The packability of airbag fabrics is an important parameter. Good packability is essential if the airbag is to be accommodated in the steering wheel or in the dashboard in the least amount of place. In addition, good packability also helps in the smooth inflation of the airbag during deployment.

Further to the tests listed in the above table, other tests followed for coated airbag fabrics include adhesion, softness, curling property and inflation tests [166]. Adhesion tests can be performed in a Scott crumbling tester using 1000 cycles at a pressure of 2 kgf, followed by microscopic inspection of the exfoliation of the coated membrane on the fabrics surface. Softness can be tested by the cantilever method (45°) in the longitudinal and transverse directions with the coated side of the fabrics facing upwards. The curling property can be evaluated by conditioning a coated fabric (area = 20 cm^2) with the coating facing upwards and evaluating the curling under microscope. Airbag inflation testing can be done by blowing hot air at 170–180 °C under a pressure of 7–8 kg/cm^2 and microscopically observing the exfoliation of the coating during the inflation.

The airbag fabric should pass the quality tests listed in Table 11 and should have a self-storage life of 10 years or more without substantial deterioration. Generally, the airbag fabric should have a thickness of less than 0.016 inches (0.06 mm), a weight in the range of 180–250 g/m^2, breaking strength of 1300 N or more and trapezoid tear strength

Table 12. Properties of airbag fabrics.

Research group	Weight (g/m^2)	Tensile strength warp/weft	Tear strength warp/weft	Air permeability
Krummheuer et al. [118]	–	3330/3100 N	130/133 N	4.9 L/dm^2/min @ 500 Pa
Bowen et al. [137]	200	530/512 N	92/79 N	–
	285	755/760 lbs/inch	179/200 lbs	–
	235	562/551 N	135/114 N	–
Kim et al.[108]	–	220 kgf/inch	34 kgf	1.2 CFM
Beasley [136]	–	–	–	1–4 CFM
Kesshavraj et al. [153]	85–510	100–750 lbs/inch	100–750 lbs/inch	–
Debenedictis, & Schmitt [149]	246	1929/2058 N (grab method)	251/259 N (tongue tear)	10 L/dm^2/min (static) 670 mm/sec (dynamic)
Kim et al. [106]	–	235 kgf/inch	15 kgf	1.4 CFM
Schmitt & Debenedictis [150]	215	227 kg (grab method)	10.9 kg (tongue tear)	178 cc/sec/cm^2
Schmitt & Debenedictis [150]	214	234 kg (grab method)	12.4 kg (tongue tear)	211 cc/sec/cm^2

of 180 N or more. Table 12 shows some of the properties of airbag fabrics determined by various research groups.

The airbag needs to be folded and packed in a small space for a long period of time without any deterioration or blocking and sticking. Some tests specify 75% of property retention after 4000 hr at 90–120 °C or the equivalent of 10 years of UV exposure. These tests are designed to ascertain the ageing property (physical and chemical changes) of airbags by external factors.

Coated airbags are tested for coating weight and coating adhesion (by the CRE tester). The degree of surface tackiness is measured by a blocking test when the two materials are placed face to face under specified conditions. For the flammability test, the fabric is subjected to bonfire test simulating an actual car fire. Airbag performance testing is done on a test rig that resembles the airbag mounted in the car. The apparatus produces a graph of inflation time after the crash with the help of in-built sensors. A video camera is used to record the changing geometry of the airbag.

In some instances, suitable modelling techniques can be used to study the effect of various input test parameters on the performance of the final fabrics [218,229,237]. For example, neural network architecture was used as a design tool in determining the permeability and biaxial stress–strain relationships for textile fabrics used in airbags [144,238]. A blister inflation technique was used to obtain the experimental permeability values under biaxial strain conditions, which were used to train the proposed network architecture. The blister inflation technique provides an analogue for stretching behaviour similar to the actual airbag deployment [239]. The two mechanisms by which the energy is absorbed by a deployed airbag are inelastic fibre stretching and viscous airflow through the fabric [239]. Both of these mechanisms can be quantified by the novel blister inflation

(a) (b)

Figure 23. Components of inflator assembly: (a) initiator and (b) micro gas generator.

technique. The predictions obtained from the neural network model agreed well with the experimental data.

3.3.2. Testing of other assemblies

During the in-house production of various airbag assemblies, automated inspections are made at several stages of the production line to identify faults. For example, radiography is used by an airbag manufacturer to compare the completed inflators with a master configuration stored in the computer. Inflators without the proper configurations are automatically rejected by the system.

Computer simulations can also be performed on airbags in parallel to physical tests, for a variety of product configurations. For other airbag components, computer simulation is an economical and time-efficient alternative to physical testing, which is based on the information and crash test patterns developed through long-term research and development. Several computer crash simulations are performed in tandem while performing the crash tests. These test results are widely used by vehicle manufacturers, auto suppliers, safety organisations and trade magazines.

Generally, sodium azide pellets are received from external vendors and inspected as per the specifications. These pellets are stored in a safe storage place after inspection until needed. The oxidisers are also received from external vendors, inspected and stored. The sodium azide and the oxidiser are then taken from the storage and blended carefully under advanced computerised process control. As there are the chances of possible explosions, the blending is performed in isolated bunkers. When a spark is detected by high-speed deluge systems, the whole room is doused with water. The production process is carried out in several redundant smaller facilities so that if an accident occurs, only that facility is closed temporarily. After blending, the propellant mixture is compressed into disc or pellet form by presses and sent to storage.

The inflator components, such as the metal canister, the filter assembly and the igniter, are received from external vendors and inspected for adherence to specifications and various performance parameters. The other important parts include initiators and micro gas generators (Figure 23). An initiator is a device which triggers the gas discharge in pyrotechnic airbags. Electrically triggered initiators are used in modern cars to provide a reliable and tuneable ignition for individual airbag shapes. Micro gas generators utilise an inflation method similar to their larger airbag counterparts.

The inflators are two-terminal devices in metal housings, which are used to initiate the airbag deployment in an automobile crash. Dual inflators are used in modern passenger cars for variable inflation rates, depending on the speed of the crash. One inflator is used for low-speed crashes and the other is used for high-speed crashes.

The inflator is assembled in automated production lines by combining the inflator components with the propellant and an initiator. Stainless steel inflator components are joined by CO_2 gas-based laser welding, whereas aluminium inflator components are joined by friction inertial welding. In laser welding, laser beams are used to join the components together, but in friction inertial welding two metals are rubbed together until the surfaces are joined together by the heat generated by friction.

The performance of an airbag during development is assessed by the closed bomb test and discharge tank test [240]. The performance of the propellants is assessed by the closed bomb test. This test is done in a closed vessel by loading the propellant and the initiator. The propellant is ignited by an electric signal and the combustion characteristic of the propellant is studied from the pressure data. The performance of the airbag assembly is investigated by the discharge tank test. In this test a constant volume discharge tank is used in place of an actual airbag cushion. An inflator placed in the discharge tank is activated with an electric signal. The gas ejection performance of the inflator is investigated from the pressure data in the discharge tank.

The inflator assemblies are inspected and stored in appropriate storage until needed. The tested inflator assembly is then mounted with the airbag assembly. Finally, the whole module assembly is carefully inspected for any faults. Subsequently, the airbag is folded into the desired shape and the cover is installed. Before shipment, the completed module assemblies are packed in boxes, labelled and sent to the customers.

During the airbag production, the inspection and quality control are very important as the safety features of airbags rely on this. The propellant or pyrotechnic ballistic tests and the airbag and inflator static and dynamic tests are the two major quality control tests. The performance of the propellants is tested by ballistic tests before they are packed into the inflators. During the test, a representative number of test specimens are selected from the population and tested on a full-scale inflator test. The test measures the ability of an inflator to produce the required amount of gas at a given rate for the proper deployment of the airbag.

3.3.3. Performance testing

After analysis of the products and the computer simulation tests, the performance of a complete restraint system can be tested in the laboratory. The airbags are tested under various conditions with or without dynamic loading. Then, the computer simulation models are validated based on the performance testing results. The performance of an airbag is a crucial issue in the incident of a collision. The airbag must inflate and cushion the occupant in a collision. Hence, different tests such as static deployment, OOP deployment and full-vehicle chamber deployment are performed before fixing them into the vehicles [14].

Figure 24 shows a flowchart that describes the test sequence followed for airbag performance testing. In this test, cars weighing up to 3.5 tonnes are used at speeds up to 50 mph. These test procedures comply with European Standards. This figure indicates that the airbag manufacturers have to handle many aspects of testing starting from test method development, pretest preparations and computer simulations to crash testing,

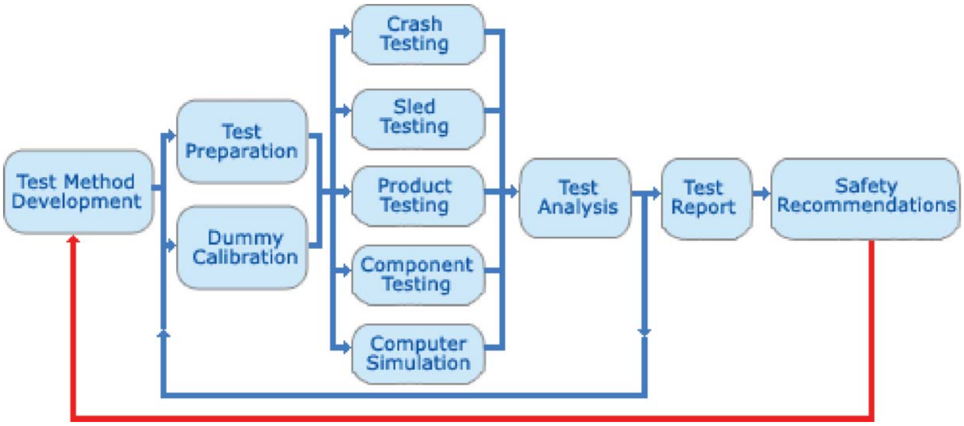


Figure 24. Flow chart for performance testing of airbags (Courtesy: Autoliv).

post-test analysis and safety improvement recommendations. Two major tests used for the performance testing of airbags include sub-system sled testing and vehicle crash testing as described below.

3.3.3.1. Sub-system sled testing. After verifying the product performance, the whole restraint system is verified in a crash test. Instead of destroying a complete car in a crash test, the stripped vehicle body is reinforced and placed on a sled. The recorded crash pulse for the simulated car is accurately repeated by braking the sled with a combination of energy-absorbing iron bars or by accelerating the vehicle. The destroyed interior materials are replaced and the reinforced vehicle body is repeatedly used for a number of car-like crashes, which reduces the cost of testing. The sled test used for airbag performance is shown in Figure 25.

3.3.3.2. Vehicle crash testing. In the crash test, the restraint systems are tuned before the system performance is verified during the test. Velocities up to 80 km/hr can be used in

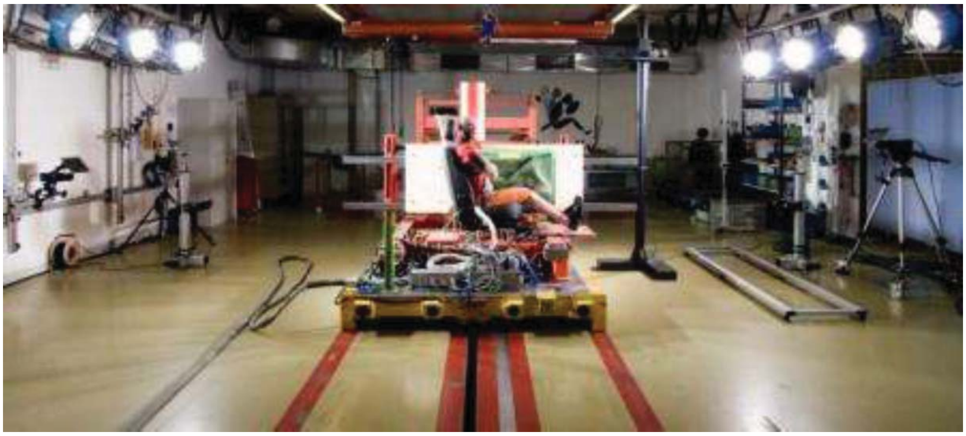


Figure 25. Sled test used for airbag performance.

Figure 26. Vehicle crash testing used for airbag performance.

the impacts with tow masses up to 3.5 tonnes. Different tests can be performed depending on the specific requirements of the car manufacturer or governmental regulations, which include flat barrier impact, angled barrier impact, offset barrier impact, pole barrier front or side impact, under-ride barrier impact, mobile barrier, side or rear impact, car-to-car, side or rear impact and rollover impacts. The performance testing of airbags in crash test is illustrated in Figure 26.

A fully computerised crash control system, known as the nerve centre of the entire operation, is used for the supervision of the sled and vehicle crash tests from a control room. Sensors, cameras, towing, acceleration, velocity, test input data and other relevant parameters can be set and monitored from the crash control system. The control system can abort a test instantaneously if any element in the testing system is not operating perfectly. The testing can be viewed by the clients from a well-equipped observation room.

The modelling of airbag focuses on the performance of various airbag designs, folding types and the interaction of an airbag with an occupant during a collision. The simulation studies involve the formulation of a series of mathematical equations to model the motion of the airbag during occupant interaction. Various software such as LS-DYAN® are used for the modelling of the airbag crash. Various models such as the Cornell Occupant Kinematics Model, can quickly process the data. Once the modelling is complete, the simulated results are compared with the experimental result; in successful modelling, there will be good correspondence between the two sets of numerical data.

3.4. Chemistry of airbags

The gas generators in modern airbags can be based either on pyrotechnic or augmented devices, depending on the configuration used to produce and deliver the amount of gas required for inflating the airbag. The pyrotechnic inflators (discussed later) produce the gas rapidly from solid propellants, whereas augmented device inflators (Figure 27) dilute the hot and high-pressure gaseous products from propellant combustion, before discharging into the airbag [241–243]. The airbag gas generators require minimal variation in output over a wide range of operating temperatures ($-40 < T$ (°C) < 45) to achieve a consistent discharge flow rate [244]. The advantages of augmented inflators over conventional pyrotechnic inflators are:

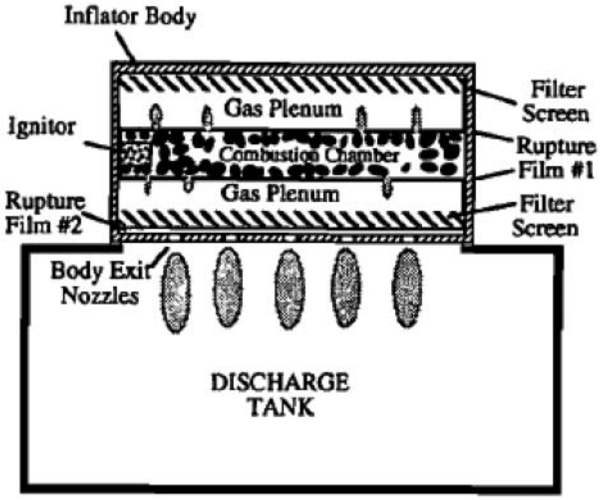


Figure 27. The cross-sectional view of an augmented inflator.

- Reduced propellant mass requirements due to the lower mass of pressurised gas stored in the unit.
- Lower average temperature of the gas mixture discharged into the airbag.
- Less dependence on the variations in the ambient-temperature.
- More uniform performance under hot and cold operating conditions.
- Dilution of any unwanted gases generated by the propellant.

In an augmented inflator, the pyrotechnic igniter and the solid propellants are located in the interior combustion chamber, which is sealed hermetically from the rest of the inflator by a thin rupture film. This film acts as a guard against moisture leakage and a means to achieve volumetric confinement of the propellant gases for the first few milliseconds following ignition. The augmented inflators rely on the compressed gas to deploy the airbag. In order to compensate the cooling effect that arises from the expansion of the compressed gas when the airbag deploys, the augmented inflators use an internal pyrotechnic heating device. The augmented inflators can be tailored to meet a wide performance range for single- and dual-stage airbags.

The gas(es) used to fill the airbag must be non-toxic, odourless and cool enough to avoid burn-related injuries to the occupants. In addition, the gas(es) should be stable, should not expand unexpectedly and be safe to dispose off. First-generation airbags used a canister of pressurised gas stored at ambient temperature [245]. In modern cars, the two types of gases primarily used for the airbags are nitrogen (N_2) and CO_2, although some other gases or gaseous mixtures are being used.

3.4.1. Nitrogen-based airbags

The most common inflators used in airbags are pyrotechnic based, which produces a harmless gas during the airbag deployment. The most common propellants in

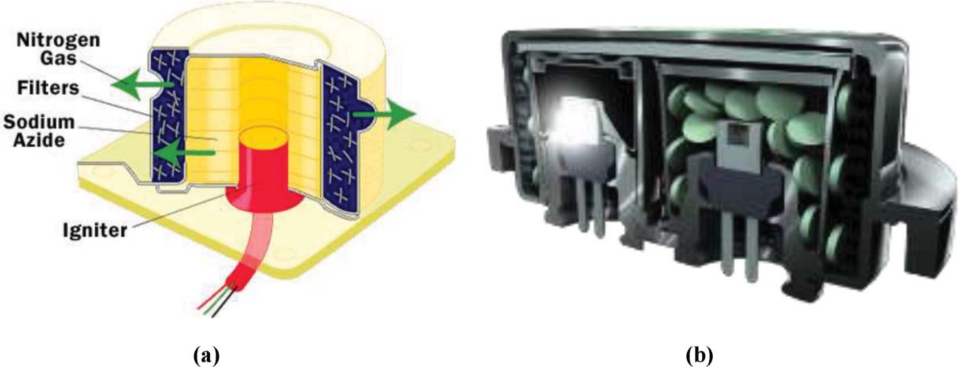


Figure 28. The inflators used in pyrotechnic airbags: (a) schematic diagram and (b) actual image (Autoliv inflator).

pyrotechnic inflators of recent airbags are azide based (e.g. sodium azide (NaN_3) with metal oxide oxidisers (potassium nitrate (KNO_3) and silicon dioxide (SiO_2)). Azide-based propellants are preferred over others because of their low flame temperatures, and their gas-phase combustion products consist of a large percentage of harmless nitrogen gas. However, in addition to the desired nitrogen gas, a considerable condensed-phase residue is produced which must be filtered prior to inflating the airbag. A typical azide-based airbag can produce nitrogen and condensed-phase residue on a 1:1 mass ratio at an adiabatic flame temperature of approximately 927 °C. In addition, azides can exhibit ignition difficulties and non-homogeneous characteristics.

Most of the pyrotechnic inflators are aluminium-encased units containing an igniter (squib), gas generant pellets (NaN_3) and filters [32] (Figure 28). Sodium azide combined with an oxidiser and SiO_2 is used as the propellant and is located inside the inflator canister between the filter assembly and the igniter. The driver side airbag contains about 50 g of NaN_3 in a canister whereas the passenger side airbag contains about 200 g. During a crash, the gas generant is ignited by the igniter and produces the harmless nitrogen gas as it burns. This gas is then forced through the filters in the inflator, which cool the gas and remove particulate matter. As the gas exits the inflator, it enters the airbag cushion, deploying it in time to protect the vehicle's occupants.

In pyrotechnic inflators, compounds such as zeolite can be used to reduce the temperature and to scavenge at least a portion of the toxic compounds [246]. In addition, the burn rate modifiers such as alkaline metal nitrates (NO_3^-) or nitrites (NO_2^-), dicyanamide or its salts and sodium borohydride ($NaBH_4$) can also be used.

Nitrogen is an inert gas and its behaviour can be approximated as an ideal gas at the temperature and pressure of the inflating airbag. In the event of a crash, signals from the deceleration sensor ignite the gas generator mixture by an electrical impulse, creating the high-temperature conditions necessary for NaN_3 to decompose. A series of three chemical reactions produces N_2 gas inside the gas generator and rapidly fills the airbag. The three reactions can be defined as (1) decomposition of NaN_3, (2) reactions to remove harmful products and (3) reaction stoichiometry.

Reaction 1: $$2NaN_3 \rightarrow 2Na + 3N_2$$

It is worthy of note that NaN_3 is highly toxic and the allowable limit in workplace is 0.2 mg/m^3 of air. Sodium azide is a stable solid and the small pellets can be easily stored in the airbag module; however, sodium azide can decompose at 300 °C to produce sodium (Na) metal and N_2 gas. The sodium metal thus released is highly reactive and potentially explosive, so this is removed by KNO_3 and SiO_2 and converted into harmless by-products. In the second reaction, the sodium metal reacts with KNO_3 to produce potassium oxide (K_2O), sodium oxide (Na_2O) and additional N_2 gas.

Reaction 2: $$10Na + 2KNO_3 \rightarrow K_2O + 5Na_2O + N_2$$

The N_2 gas generated in the second reaction helps to fill the airbag whilst the metal oxides react with the SiO_2 in a third reaction to produce a harmless and stable alkaline silicate glass. The metal oxides, K_2O and Na_2O are highly reactive and cannot be allowed to be left as a product of airbag detonation.

Reaction 3: $$K_2O + Na_2O + SiO_2 \rightarrow Na_2K_2SiO_4 \text{ (alkaline silicate glass)}$$

The potential for direct human exposure to sodium azide has been increased in operations such as transportation, assembly, manufacturing, repair and scraping due to its use in automobile airbags. The handling of sodium azide and its mixtures must be carefully controlled due to issues related to its toxicity and combustibility. The common health hazards from azide exposure are hypotension, nausea, vomiting, diarrhoea, headache, dizziness, dyspnoea, palpitation, temporary loss of vision, temporary loss of consciousness or decrease in mental status [247]. Severe symptoms include seizure, arrhythmia, coma, tachypnoea, pulmonary oedema, metabolic acidosis and cardio-respiratory arrest. The absorption of sodium azide in significant doses either in laboratory conditions or during airbag manufacture or by skin contact during accidents is life threatening.

In addition, the disposal of sodium azide increases the potential for contamination of the environment. Azides are highly water soluble and are stable in solutions that are neutral to basic pH in the absence of light, but if exposed to sunlight, photolytic decomposition will begin, which can produce metal nitrides initially, followed by the formation of the free metal and nitrogen gas [248].

Although sodium azide propellant produces a breathable gas, it has some drawbacks such as: (1) contact of water/azide mixtures with the human skin tends to lower the blood pressure, (2) contact of water/azide mixture with heavy metals, especially copper or lead, can result in the formation of volatile explosives [249], (3) the disposal of undeployed airbags is a concern as NaN_3 is a toxic chemical, (4) the metallic sodium produced during the deployment reaction is very reactive, which necessitates the use of other compounds such as iron oxide (Fe_2O_3) to neutralise its effect and (5) NaN_3 reacts with water and forms hydrazoic acid (HN_3), which is highly toxic, volatile and explosive, and so it must be kept dry (Reaction shown below).

$$NaN_3 + H_2O \rightarrow HN_3 + NaOH$$

3.4.2. CO_2-based airbags

CO_2-based airbags use a mixture of sodium bicarbonate ($NaHCO_3$) and an aqueous solution of acetic acid (CH_3COOH) to produce CO_2 gas. The CO_2 gas is released instantly to inflate the airbag as shown in the following reaction:

$$NaHCO_3(S) + CH_3COOH(Aq) \rightarrow CO_2(G) + CH_3COONa(Aq) + H_2O(L).$$

In many stored-gas airbags, a cylinder containing compressed CO_2 is used for the inflation of the airbag. The airbag is deployed by the release of the CO_2, when the sensors trigger the deployment condition.

3.4.3. Other airbags

The majority of commercial airbags are azide based, but due to the hazards involved with sodium azide, several other alternative approaches using non-azide propellants have been explored. Recent non-azide pyrotechnic propellants are smaller, lighter than before and are available for driver, passenger, side and knee bolster airbag applications. Examples of non-azide propellants currently used for airbags are nitrocellulose-based substances [250–253] and cyclotrimethylenetrinitramine (RDX)-based propellants [254]. Nitrocellulose inflators do not need filters, are less expensive and less toxic [246].

These propellants are added with other chemicals such as binders, plasticisers, stabilisers, anti-oxidising agents and other unique processing aids. Although these propellants produce significantly less slag, they burn at much higher flame temperatures; hence an appropriate method has to be adopted to reduce the temperature before the airbag interacts with the occupant. These products generate a gaseous mixture of N_2, CO_2 and water with some minor undesirable gases such as CO and nitrogen oxides (NO*x*). Some of the non-azide propellants can generate 100% gas-phase products eliminating the costly requirements of slag filtration.

A non-azide propellant composed of a mixture of azodicarbonimide, potassium perchlorate ($KClO_4$) and cupric oxide (CuO) was selected to replace the traditional azide-based propellants [244]. This propellant mixture is relatively safe and environmental friendly and has been reported to have satisfactory performance required for airbag deployment. The drawback of this propellant is its tendency to produce high levels of CO and NO*x*. Several modifications such as changing the propellant chemistry and use of catalyst were investigated to reduce the levels of CO and NO*x* to acceptable limits. For example, a dual-chamber combustion technique was used to reduce the CO levels by converting it to CO_2 as it flowed from the combustion chamber to the pressurised plenum before being discharged.

Some of the other non-azide gas generators are based on organic compounds such as nitroguanidine, triaminoguanidine nitrate, guanidinium azotetrazolate, ammonium perchlorate/guanidine nitrate/sodium nitrate and 5-aminotetrazole [255–258]. These formulations are chemically stable under extreme hot and cold conditions, and the level of toxic compounds in solid material and the product gases does not exceed the specification level. They can be ignited easily and the burning rates can be varied easily to produce the required gas.

The use of steam to fill the airbag is also being reported [259]. The airbags use heated and pressurised water stored in a rigid container. During a crash, the container opens rapidly and the water is converted into steam due to the fast depressurisation. The system can be referred as “steam bag” as it requires only water and heat without any chemical substances. Some other inflators use stored nitrous gas, argon or helium or other harmless gases to inflate the airbags.

Another type of inflator includes hybrid technologies, which use a combination of compressed gas and solid propellants. Hybrid inflators that store pressurised gas and a small amount of pyrotechnics were developed to overcome the difficulties of handling pyrotechnic material [32,260]. Hybrid inflators are only warm when deployed compared to the pyrotechnic inflators, which become very hot. Hybrid inflators can be designed to inflate in two stages of the airbag deployment simultaneously or separately.

4. Airbag operation

In an impact zone, one or more airbags are deployed by the sensors at variable rates based on the type and severity of the impact. The airbags are designed to inflate only in moderate to severe crashes. The sensors of the airbag system sense that the crash is severe enough to trigger the operating mechanism of airbags. The mechanism initiates the reaction that generates the required gas to inflate the airbag cushion on time. The cushion prevents the occupant accelerating forward to hit the dashboard or steering wheel. In most crashes, the firing, inflating and deflating of the airbag cannot be noticed due to the impact and noise of the crash. Following the deployment, the airbag cushion deflates immediately.

The output of an inflator can be tailored as per the requirements of the restraint system. The bag cushions the occupant's impact via pneumatic damping effects produced by the airbag fabric and any specially constructed vents in the airbag. The exit temperature of the gas leaving the inflator depends on the heat transfer between the gas and the filter. During the inflation processes, the gas temperature is reduced to a safe level by the filter to prevent the airbag from damage by the high-temperature gas. The top view of the deployed driver, passenger and side-impact airbags are shown in Figure 29.

The airbag is made with provisions of openings/venting holes from which the high-pressure gas is exhausted after the deployment. These venting holes must be precisely sized to allow controlled deflation of the airbag. The deflated driver and passenger airbags after a collision are shown in Figure 30.

4.1. Airbag deployment

In the event of a crash, the modern smart airbags will automatically inflate to their full volume. However, in some instances, depending on the severity of the crash, the bag can

(a) (b)

Figure 29. The deployed airbags: (a) driver and passenger airbags and (b) side-impact airbag.

Figure 30. The driver and passenger airbags after deployment.

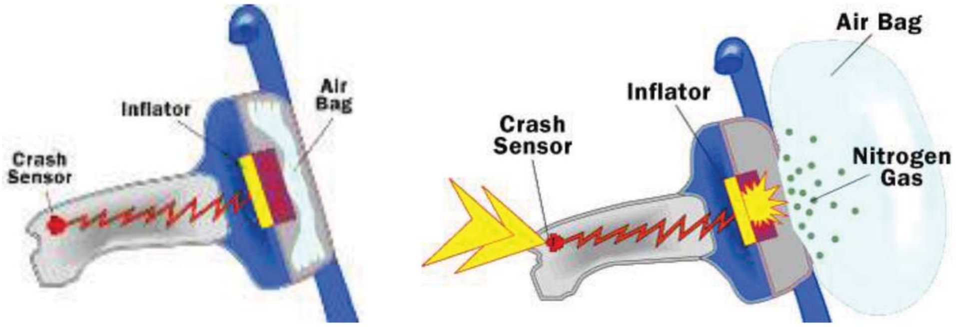
expand to higher volumes by rupture of an extra “tear seam” and absorb more energy. For example, the driver side airbag can expand from 45 to 65 L by the rupture of the tear seam in the Ford car models. The airbag deploys through the module cover at a specific speed and angle depending on the crash conditions.

4.1.1. The mechanism

The mechanism of airbag deployment is rather complex is that it depends on the size and location of the occupant and type and severity of the crash. The following section describes the detailed mechanism of airbag deployment.

4.1.1.1. Triggering conditions. In the incident of an airbag deployment, the level of crash severity is called the “deployment threshold”. For example, in the Ford models, airbags are designed to deploy at frontal impact speeds over approximately 23 km/hr in a head-on collision into a solid barrier under normal conditions. The deployment threshold is also governed by the regulations for vehicle construction as per the particular market segment the vehicle is intended for. For example, US regulations require the deployment of airbags of passenger cars in frontal and near-frontal collisions at least a deceleration equivalent to 22.5 km/hr or striking a parked car of similar size across the full front of the vehicle at about twice the speed. International regulations are performance based, rather than technology based. Hence, the airbag deployment threshold is a function of overall vehicle design and the regulations for vehicle design.

Earlier airbags were designed to deploy after meeting or exceeding a specific deployment threshold. However, the modern airbag restraint system is not designed to deploy in every crash. The crash sensors determine the severity of the crash as well as the position of occupants and other significant information about the passenger compartment environment. It should sense before the occupant has moved to a position where he/she is going to interact with the deploying airbag, and it must do so before the occupant has already impacted with the interior of the vehicle [261].



(a) (b)

Figure 31. The airbag module: (a) before deployment and (b) during deployment.

A central module receives the sensory inputs and determines the necessity of deployment. If airbag deployment is necessary, the central module will transmit a current that will ignite the pellets of sodium azide, producing nitrogen gas on burning, to fill the airbag (Figure 31). The gas then gets filtered and enters the airbag cushion through the inflator ports. The airbag is inflated by the pressurised gas and is deployed through the steering column cover or passenger dash panel or other similar openings depending on the type of airbag. The airbag should deploy in such a way that it decelerates the occupant gradually so that the occupant suffers minimal or no injury. The airbag module cover is flung upwards and outwards at an average velocity of 230 km/hr. The speeds at which the airbag punches through the module door can be up to 320 km/hr. The airbag is fully inflated within 40–50 msec after the airbag is triggered [262].

In the case of a longer duration impact (e.g. rollover incident), the airbag cushion must inflate quickly under high pressure (about 40–50 psi) and remain inflated at relatively high pressure in order to provide the highest degree of protection. Hence, the requirements of airbags for frontal and rollover crashes are different.

As the vehicle decelerates rapidly in a crash, airbags must inflate very rapidly to reduce the risk of the occupant hitting the vehicle's interior. In the newer designs, the frontal airbags are deployed in less than 50 msec [45]. Similarly, the side-impact airbags have to be fully deployed within 15 msec, which is eight times faster than the blink of an eye. The deflation of the airbags begins immediately after the deployment as the gas escapes through the vent holes in the airbag fabric [263,264]. A frontal airbag becomes almost empty after approximately 1 sec of the deployment.

The airbag deployment is controlled by a passive ECU located in the middle of the vehicle, where it is well protected. The ECU consists of a crash sensor and a microprocessor. This unit is known as the electronic brain of the airbag module as it determines if and when each of the airbags should be deployed [265]. In addition, it also controls the seat belt pre-tensioners and retractors automatically by removing the slack and positioning the occupant for maximum airbag protection when the airbags are triggered [266,267].

The ECU receives information from the sensors (such as accelerometers) mounted in key locations inside the vehicle. The accelerometers measure the deceleration rate and activate the airbag(s) depending on the severity of the collision. The airbag accelerometer is a microelectromechanical system (MEMS), which is the combination of miniaturised

Figure 32. Operating switch to turn off the airbags.

mechanical and electromechanical elements (i.e. devices and structures) that are made using the techniques of microfabrication. It consists of a small integrated circuit with integrated microelectromechanical elements. The microelectromechanical element moves in response to rapid deceleration, which causes a change in capacitance. This change is detected by the electronics on the integrated circuit, which sends a signal to trigger the airbag. The most common MEMS accelerometer in use is Analog Devices' ADXL-50, although there are several other manufacturers.

During a crash, the rapid deceleration (of about 20 km/msec) leads to airbag deployment by triggering a series of sensors located in the front bumper. Passengers closer than 25 cm to the airbag during deployment are at risk of serious injury. Children and shorter people (under 157 cm) with their seats closer to the dashboard/steering wheel and unrestrained passengers are projected quickly towards the front face of the vehicle interior and are at particular risk of injury.

In a survey it was found that the median impact velocity at which the European and American airbags deployed was less than 20 km/hr. However, a review by Holden's safety experts in Australia found that the airbags in Australian cars deploy less aggressively than in American cars.

Airbags are designed not to activate during sudden braking or while driving on rough roads or uneven pavements. In fact, the most severe braking is only a small fraction of the deceleration necessary to activate the airbag system. Several researches have been done to simulate airbag inflation including the overall airbag wave form, by using airbag inflation models constructed around hydrodynamic and thermodynamic theories [268]. However, the performance of the fabric material during deployment is completely ignored because of the complexities involved in modelling fabric deformations.

In some cars, there is a provision to turn off the airbags by operating a switch (Figure 32). The airbags can be deactivated if the occupants are children or of small stature. This also depends on the prevailing regulations on the airbag use in the specific region.

Unlike crash tests with barriers, real crashes typically occur at varying angles rather than directly into the vehicle front and the impact forces are usually not evenly distributed across the vehicle front. Hence in a real crash, the relative speed between a striking vehicle and the struck object required to deploy the airbags can be much higher than in an equivalent barrier crash test. Vehicle speed is not a good indicator to decide whether an airbag should be deployed, as airbag sensors measure deceleration; sometimes, therefore, airbags can deploy due to the resulting deceleration when the vehicle's undercarriage strikes a low protruding object above the roadway.

Almost all airbags are designed to deploy automatically in the event of a vehicle fire when the inside temperature reaches 150–200 °C. This safety feature, known as auto-ignition, confirms that such temperatures do not cause an explosion of the entire airbag module.

4.1.1.2. Variable-force deployment. Modern airbags are designed to tailor the airbag deployment depending on the severity of the crash, the size and posture of the vehicle occupant, the seat belt usage and proximity of the occupant to the airbag. Several airbag systems use multi-stage inflators that deploy less aggressively in several stages in moderate to severe crashes. Occupant sensing devices can sense different conditions such as the weight of the person, whether the occupant is occupying a seat adjacent to the airbag, whether a seat belt or child restraint is being used and whether the person is close to the airbag; they transmit the information to the airbag control unit. Based on this information and crash severity, the airbags are deployed either with high force or at a less forceful level or not at all.

Multi-stage airbags are used in adaptive airbag systems to adjust the pressure within the airbag. The higher the pressure within the airbag, the more force will be exerted on the occupants by the airbag as they come in contact with it. These systems deploy the airbag with moderate forces for most collisions while the maximum force airbag is only deployed in the most severe collisions. Additional sensors are used to determine the location, weight or relative size of the occupants. The airbag control unit receives the information related to the occupants and the severity of the crash, and determines whether the airbags should be suppressed or deployed, and if deployed, at what output levels.

4.1.2. Lifesaving ability

The combination of seat belts and airbags is 75% effective in preventing serious head injuries. When an automobile crashes, the vehicle itself comes to rest rapidly. However, if unrestrained, the occupant's body in the vehicle continues to move forward at the same velocity as the vehicle was travelling before the collision and comes to rest when it hits some object such as the steering wheel or dashboard or the seat in the front (Newton's first law of motion). The force exerted on the body to reduce its velocity causes the injuries. Airbags protect the body by applying a restraining force to the body that is smaller than the force, the body would experience if it hits the dashboard or steering wheel. According to Newton, the force (F) of a moving object is given by the equation:

$$F = m \times a,$$

where m = mass of the object (body) and a = acceleration. If $F > 0$, the body is accelerating, and if $F < 0$, the body is decelerating. The acceleration "a" is given by

$$a = V/\Delta t,$$

where V = velocity of the moving object and Δt is the time interval for the body to go from V_i (initial velocity = velocity of the vehicle at the time of collision) to V_f (final velocity = 0 m/sec as the body comes to rest). Hence, in this case,

$$a = -V_i/\Delta t.$$

Here, V_i is negative as the body is decelerating. Now the force exerted by the steering wheel (i.e. an immovable object) on the body to bring it to rest is

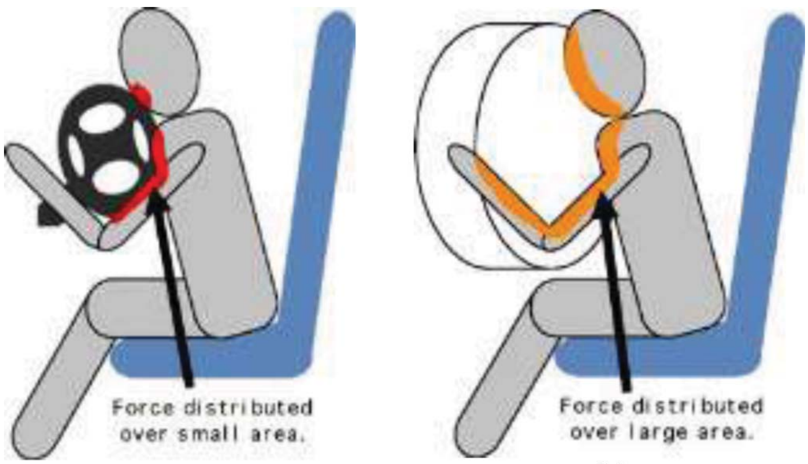
$$F = m \times (-V_i/\Delta t).$$

This is the force that causes injuries to the body in an accident, and it can be reduced by the airbags in two ways:

(1) By spreading the force over a large area of the body so that the force per unit area (pressure) on any particular part of the body is reduced.
(2) By increasing the time interval (Δt) over which the decelerating force is being applied.

When an airbag or the steering wheel (say) is restraining the body from moving further forward just after the collision, the body exerts an equal and opposite force against the steering wheel or the airbag (some steering wheel assemblies are made to be collapsible under collision conditions to improve driver safety, but not in this example). Unlike an immovable and rigid steering wheel whose narrow profile would impact with the body in very localised regions, being large and flexible, the airbag can spread the force over a large area of the head and body whilst in addition, it deflates slowly due to the presence of vents in the airbag. The force exerted by the body pushes the gas through the vents and thus deflates the bag. Because the venting gas can only leave at a chosen rate, Δt, the time interval over which the decelerating force is applied to the body is increased (an effect with some common features with the crumple zones in automobile body designs).

In other words, if the body crashes directly into the steering wheel and/or dashboard, all of the braking force on the head and body will be applied by the steering wheel and/or



(a) (b)

Figure 33. The relative force distribution on the body: (a) without airbag and (b) with airbag.

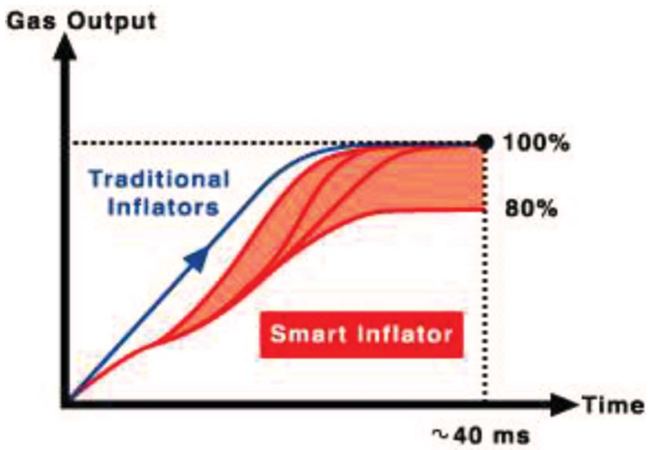


Figure 34. Working of smart inflator compared to traditional inflator.

dashboard to localised areas, much smaller in size than those covered by the airbag and serious injuries can occur. However, when the body hits an airbag, a much larger, flexible area is available to be pushed against, and the force of the body moving forwards will be distributed over this large area of airbag, thus reducing the pressure on any particular point on the body and avoiding more serious injuries. As this takes place, venting of the gas lets the airbag deflate steadily which reduces the effects of impact in another way by slowing down the body's deceleration. In ideal circumstances:

- The airbag spreads the force from impact over a large area reducing its effects on specific parts of the body.
- The vents spread the force from the impact over time reducing its effects on the whole of the body.

This phenomenon is described schematically in Figure 33.

The earlier versions of airbags were designed to deploy with a fixed volume of gas output irrespective of the type and severity of a crash. However, the smart inflators in recent cars monitor the type, severity and duration of the crash. The volume of gas output can be tailored to meet the requirement of deployment force as shown in Figure 34.

4.1.3. Injuries caused by airbags

Half a million persons are killed on the roads worldwide every year and road accidents are becoming one of the top three causes for premature death. Airbags and associated safety devices have become one of the largest growth areas in technical textiles over recent years. Although, airbags significantly reduce the risk of serious or fatal injuries in accidents, there exist some risks of their deployment [269,270]. The vast majority of injuries (96%) are minor injuries categorised as bag slap injuries such as grazing, bruises and abrasions to the face, neck and upper limbs [197,271]. However, it has been shown that airbags cause potential hazards to children [272] and small stature occupants in the front seat [273,274]. The other airbag injuries to adult occupants include periorbital fracture, head injuries, eye injuries [275,276], internal organ lacerations, cervical spine injuries and otologic injuries [277]. In addition to the minor and severe injuries, deaths of adult occupants have also been reported.

In frontal impacts, the mass and position of a driver in relation to the steering wheel are the key elements affecting the nature and severity of the injuries [278,279]. The probability of smaller drivers striking the steering wheel is higher as they are normally seated closer to the steering wheel [248]. If the driver is sitting closer to the steering wheel, it becomes difficult for proper deployment of the airbag without causing any injury. On the other hand, if the driver is located at longer distances, he/she attains a greater relative velocity prior to hitting the airbag. This coupled with the chance of hitting an airbag that has already started to deflate, increases the chance that the taller and heavier driver will hit the steering wheel after passing through the deflated airbag. Hence, it is essential that the driver does not hit the airbag while it is in its early stages of deployment or when it is already deflating.

The airbag-induced injuries become more severe when a person is not restrained by a seat belt or is not seated properly in the car seat or in an OOP place [280]. To avoid the risk of injury, the front seat occupants should be firmly restrained and the rear seat occupants sit consistently in proper position [281] with comfort and access to controls. The inner surface of the airbag is powdered with talcum powder in order to keep the airbag operative for many years and enable easy deployment during a crash by avoiding the sticking of layers. However, during deployment, the talcum powder along with some other particles from the coating and gas mixture are driven out of the airbag, and can penetrate into the eyes and breathing passages of the occupants causing eye and respiratory injuries [101].

The risk of occupant injuries in side-impact collisions is higher than the front- or rear-impact collisions, as the side of a passenger vehicle has only a limited ability to crumple and absorb energy during the crash [282]. In the USA, around 3.18 million passenger vehicles are involved in side crashes every year. These crashes result in about 9400 deaths, which is about 30% of all passenger vehicle occupant deaths [283]. The occupants in side-impact collisions are at the highest risk of serious chest and head injuries [284]. In side-impact crashes involving passenger vehicles, an estimated 40–75% of occupant deaths are related to the head injuries.

In vast majority of side crashes, the lack of seat belt use and pre-impact braking resulted in children being OOP in the deployment path of the airbag [273]. These OOP children receive serious and/or fatal neck and chest injuries. A study on OOP child injuries was carried out using the Hybrid III (3- and 6-year old) and the TNO Q3 (3-year old) child dummies [285]. In-position, OOP and dynamic tests were performed to monitor the interaction between the child seat and airbag to confirm that properly restrained children would avoid the undue risk from a deploying side-impact airbag. The OOP results suggested that the side-impact airbag designs may cause serious and/or fatal neck and chest injuries.

An NHTSA study investigating 32 deaths of small children, found that 9 were caused by rear-facing infant seats positioned directly on the airbag when it deployed [71]. The other common cause of death was unbelted children, including some children who were strapped in child seats that were not secured to the car. Hard braking in the case of an accident, threw them onto the airbag, causing severe injuries or even death [219]. The smart airbag system of Autoliv can detect a rear-facing child in the front or the location of a passenger near to the instrument panel before the airbag is deployed [144,281].

The revised joint Australian and New Zealand Standard AS/NZS 1754:2013 allows the use of child restraints featuring ISOFIX-compatible lower attachment connectors

[286]. The parents and guardians of young children can use the ISOFIX attachment connectors or the vehicle seat belt threaded through the child restraint in order to attach the child seat to the car at its base, to make the airbag use successful. When correctly installed, both systems offer satisfactory levels of protection although ISOFIX is better mechanised. There is also a need for education and publicity on airbags, to ensure that the seat belt use is sustained and that children are properly restrained in the back seat.

The advanced smart airbag is a tough, self-inflating cushion which expands very fast to meet the body mass of the passenger halfway, then decelerates the body within survival parameters [287]. An airbag provides a force over a specific time immediately following a collision, which is known as an impulse. The higher is the time the force is acted to slow the passenger down, the less severe is the injury caused. The time for airbag deployment is very limited as the time gap between the car hitting any object and the driver/passenger hitting the steering wheel/dashboard is very short. The following section describes the time response of various events during a crash.

- In 15–20 msec after the collision, the crash sensors decide whether or not to inflate the airbag.
- If the airbag needs to be deployed as decided by the crash sensors, it is done in about 25 msec after the crash.
- It takes about 20 msec to inflate the airbag for the passenger to land into.
- Within 60 msec, the passenger interacts with the airbag and the airbag starts to deflate.
- In the final 35–40 msec, the passenger continues to interact with the airbag as it progresses into the deflation process.

Unrestrained occupants are susceptible to airbag-induced injuries [288]. The injuries occur due to the movement of the unrestrained occupant and/or being struck by the inflating airbag during low-speed collisions. The risk of airbag-induced injuries can be minimised by designing the airbags which deploy faster when seat belts are not worn. This allows for complete inflation before the occupant moves substantially forward in the seat [289]. A fully inflated driver side airbag is about 7 inches thick. When the driver is closer than 7 inches to the steering wheel, the firing of the airbag can cause injuries. However, this can be avoided by distributing the load broadly across the airbag surface which absorbs the energy [290].

Of all the steering-wheel airbag deployments, approximately one-third resulted in facial injuries including erythemia, abrasions and contusions [262]. Other injuries related to steering wheel are upper extremity injuries (about 38% of the deployments).

The combustion of NaN_3 releases alkaline by-products, which are released into the interior of the vehicle on deflation of the airbag and can lead to chemical keratitis or ocular burns and/or visual loss. (Treatment needs to be instituted in less than 60 sec to irrigate the eye.) The presence of mobile phones, tobacco pipes or make-up containers can cause serious ocular injury if they are in use at the time of airbag deployment.

Different systems have been developed to minimise the impact of a head/torso airbag for smaller passengers and OOP passengers. Some systems use occupant sensors to turn off the airbag when the occupant is a child (3–6 years) or a person of small stature. These sensors are complicated and expensive. Other systems attempt to reduce the impact force of deployed head/torso airbag on passengers. It has been well documented that elderly people are more susceptible to injury than younger people in collisions [291]. Crash protection for the ageing population can be hampered by the societal-based approach to identify this population.

In the USA, all the new vehicles since 1994 have been equipped with airbags [292]. The researches conducted to assess their effectiveness in saving life, provide conflicting results. Although several deaths or serious injuries have been avoided by the airbags, there are documented evidences of serious injuries or even deaths occurring as a result airbag deployment [293–295]. Hence, there is increased concern that airbags may reduce mortality but increase morbidity. Airbag-related deaths can be found on the NHTSA website, where the cause of death has been assigned to various factors, both at low and high speeds.

Airbags must work for a wide range of body sizes, from children to large adults, over a wide range of automobile speeds and varying impact angles. Automotive designers must continue to try to find one airbag design that works for a wide range of conditions. Most simulation studies use a combination of techniques such as non-equilibrium thermodynamics (to simulate the detonation of the explosive charge and expansion of the gas) and finite element analysis (to simulate the inflation of the airbag). Simulating airbag inflation is an extremely complex process as several parameters are involved requiring competencies in physics, computational geometry, engineering, fluid dynamics and thermodynamics to bring them into play.

In addition to the injuries caused by airbag deployment, there are also reported cases of injuries caused during the various stages of airbag production such as production and handling of the pyrotechnic materials [296].

4.2. Post-deployment

The chemical reactions produce the required amount of nitrogen gas to inflate the airbag cushion. After airbag deployment, the cushion starts deflating immediately by the escape of the gas through the vent(s) in the fabric. Dust-like particles and non-toxic gases are released in vehicle's interior due to the airbag's deployment and subsequent deflation. Most of the dust consists of cornstarch, talcum powder or French chalk, which are used to lubricate the airbag during its deployment.

The dust-like particles and non-toxic gases released during airbag deployment can lead to irreparable cosmetic damage to the dashboard, upholstery and other interior parts of the vehicle, and other considerable damage to the mounting panel, ancillary parts and sensors by the airbag deployment [27]. Hence, the airbag and other ancillary parts need to be replaced before the car can be considered road safe again. As a consequence, the deployment of airbags in minor collisions can be a costly matter, even though there may be no injuries or much damage to the vehicle exterior. Such dust may also produce some minor irritation of the throat and eyes in many people, minor irritations which are aggravated when the occupant remains inside the vehicle for a long period of time with no ventilation. Some people suffering from asthma may face an asthmatic attack from inhaling the dust.

In older azide-based airbag designs using NaN_3 propellant, varying amounts of sodium hydroxide are always present initially. Although it is small in amount, it can cause minor irritation to the eyes and skin. However, it quickly turns into sodium bicarbonate (or baking soda, $NaHCO_3$) with exposure to air. This transformation is not 100% complete and can leave residual amounts of hydroxide ion (OH^-) from NaOH. Depending on the type of airbag module, potassium chloride (KCl) may also be present.

4.2.1. Airbag replacement

Almost all the airbags in vehicles are designed to be deployed only once. Once an airbag has been deployed, most manufacturers recommend its replacement. The replacement of airbags ensures that the vehicle is legal and safe for the driver and other occupants. While replacing the deployed airbags, in addition to replacing the airbag cushion, the airbag's sensors and springs, propellants and covers must be replaced. In spite of the airbags being compartmentalised components, they are relatively difficult to replace and the replacement of deployed airbags and ancillary parts is therefore expensive, and the replacement should be done by the manufacturer of the car.

Most modern cars have several airbags and in a collision not all of a vehicle's airbags will be deployed. Hence, the owner can save costs by replacing only the deployed airbags and components that need a replacement.

4.2.1.1. Replacement of airbag ancillary parts. In some cases, in addition to the airbags, there may be a need for the airbag's other components to be replaced. The airbag control module, impact sensor and clock spring are the most common ancillary components.

4.2.1.2. Replacement of control module. The airbag control module houses a chip board inside a metal box with sockets for wire input and output. The location for the placement of the control module differs between makes and models. The common positions include the centre console, behind the kick panel, under the passenger or driver seat or behind the steering column. Some control modules can be reset after the deployment of the airbag, whereas others need an entire replacement.

4.2.1.3. Replacement of impact sensors. The impact sensors are essential components that sense rapid deceleration during an impact and are placed in various locations within a vehicle. The impact sensors communicate with the control module and determine which airbags to be deployed and when. Often, the impact sensors are replaced after a collision or unwarranted airbag deployment (if they possess any defects) or if they have received water damage. However, in some cases, the impact sensors can be reset without any replacement.

4.2.1.4. Replacement of clock spring. As the name implies, an airbag clock spring is a specialised spring housed inside a hand-sized plastic circular casing in the steering wheel, which expands or contracts based on the turning of the wheel. The clock spring guarantees the electrical connectivity to the airbag in the steering wheel and other electrical components attached to the steering wheel (such as horn, cruise control, audio adjustment buttons or temperature controllers). In deployments, the heat generated by the inflator creates a very hot environment within the clock spring housing, which causes some connections to melt. Hence, replacement is necessary to make the car road safe.

4.2.1.5. Alternatives to airbag replacement. One simple alternative to replacing a steering wheel airbag is to replace the whole steering wheel. The cost of replacing a steering wheel is not significantly different from the cost of replacing the steering wheel airbag. In addition, the labour cost of replacing a steering wheel is often less than replacing the airbag.

4.3. Life of airbags

Like most other vehicle components, the airbag module and its components have certain lifespan. As discussed earlier, the ageing process may degrade the properties of the fabrics and hence the performance level of airbags. Therefore, some car manufacturers recommend scheduled checking and nominated component replacement after a specified period, typically from around 10 years and onwards. In some vehicles, after a specific time, the indicator light for the airbag system may be triggered and will stay on until the airbag system has been checked and components replaced where necessary.

In Europe and America, the average lifespan of a car can be assumed to be about 10 years. In the example of the airbag installed in the Volvo C30 series, first launched in late 2006, cars which have not yet reached the end of their life, it is not absolutely clear at this stage how the Volvo C30 will be disposed of or recycled at least 3 years from now. As per the recent Volvo environmental departmental data, in developed countries, the recycling rate for cars is approximately 80%, which might be assumed to be the same for the airbags. The remaining 20% materials in weight consist mainly of heterogeneous mixtures of resins, rubber, glass and textile materials which cannot be recycled.

The end of life of airbags follows the end of life of a car. The end-of-life scenario for airbags is different in different countries. In Europe and Japan, the undeployed airbags are removed from the end-of-life vehicle (ELV) prior to the vehicle shredding. The airbag cushion is shredded or recycled or used for making vacuum surge tanks. In the USA, the airbag module is shredded together with the ELV after the airbag is deployed. Volvo also recommends prior deployment inside the ELV before shredding. The recovery and recycling of secondary materials, such as aluminium, alloys and other components, follow the standard procedure. Some components, which cannot be recycled, are disposed of in land filling.

4.4. Maintenance of airbags

Inadvertent deployment of an airbag while the vehicle is being serviced can lead to severe injuries. If the airbag module is improperly installed or defective, then it may not perform as intended. The sale, transport, handling and service of airbags and system components are restricted in some countries. For example, in Germany, airbags are regulated as harmful explosives and only mechanics with special training are allowed to service airbag systems.

Some automobile manufactures (such as Škoda, Mercedes-Benz) suggest the replacement of the undeployed airbag and system components after a certain period of time to ensure reliability in a crash. In some models, expiry date stickers are attached to the door pillars. Generally, these dates fall after a 10-year life time of the car. Therefore, at this stage, airbag replacement is uneconomic compared to the negligible value of the car. On the other hand, Volvo has stated that "airbags do not require replacement during the lifetime of the vehicle". However, this does not guarantee the proper functioning of the airbag module.

5. Recent advances and concerns in airbag design

5.1. Recent developments

Different types of new airbag designs are paving their way to the automotive market with changing car models and increased safety levels. Recently, uncoated airbags have been developed to supersede the coated airbags with their inherent drawbacks of excessive thickness, inability to be folded and packed into small spaces and degradation over time. Low air permeability is essential for uncoated airbags to deploy promptly to cushion the occupant. The air permeability of the uncoated airbags is predicted and precisely controlled by advanced techniques.

Smart restraint systems have been developed, which tailor airbag deployment according to the crash severity, seat belt use, body size of the occupant and the proximity of the occupant to the airbag system prior to the deployment [32,297]. The smart restraint systems use all the information available about the crash to ensure that the restraint performance is optimised for each incident. The decision on bag firing, firing time, the amount and rate of inflation is governed by the nature and position of the occupant and the severity of the crash. In some instances, the airbag could inflate twice, if multiple impacts occur [11].

The earlier airbag designs utilised multiple mechanical-point sensing systems with the functions of crash detection, crash recognition and electrical switching for airbag deployment [298]. The mechanical sensors were not very sensitive and were unable to process the complete information related to the crash. The later sensors were electromechanical, which used only one bit of information, i.e. the overall size of the signal, and were more accurate [299]. Due to the recent studies on fatalities and injuries caused by airbag deployment, increased attention has been paid to passenger sensing (weight sensors, occupant detection sensors, etc.).

Recently, single-point electronic sensing systems have been developed and used in cars, where the detection, recognition and airbag deployment triggering functions are performed separately [300,301]. These sensors use electronic accelerometer and powerful microcontrollers and overcome the drawbacks of the mechanical sensors. Although, the single-point sensing systems do not require the use of front-mounted remote discriminating sensors, they are too slow to provide optimum occupant protection or sometimes fail to actuate the airbag when needed [299]. The excellent performance of most of today's airbag crash sensors is achieved by using multiple sensors remotely located from passenger compartment. The distributed sensing systems provide good crash discrimination, but they are costly because of the multiple sensors and installations [32]. Single-point sensors receive less information related to the impact for a deployment decision compared to the distributed sensors [302].

For the detection of side impacts, accelerometers should respond faster, as there is very little space between the occupant and surface of the door. The response time of a distributed system is 20 msec, the single-point system is 10 msec and side-impact sensors about 4 msec [303]. It has been claimed that Siemens' absolute pressure sensors are three times faster than the traditional accelerometer for side-impact detection and airbag deployment [304]. The pressure sensor is mounted inside the vehicle door cavity and it monitors dynamic pressure changes of the air in the cavity.

Recently, there has been an increase in the use of child seat sensing, which automatically deactivates the passenger side airbag if a child seat or a child occupant is detected. BMW has introduced a weight-based occupant detection system since January 1996, which detects presence of an adult passenger or a child and disables the airbag if the weight is less than 26.4 lbs in the seat [305].

The occupant sensing systems in cars today are based on different principles such as capacitance [306,307], ultrasonic [306,308] and infrared (IR) [11,306]. The capacitative sensors for the detection of driver and passenger would be mounted in the steering wheel and between the headliner and the vehicle roof, respectively. These sensors are affected by the objects with different dielectric constants than air. As conductivity of a human being is approximately 80 times more than air, the positioning of occupants' heads in the capacitance field has a significant effect on the detector. The system does not deploy the airbag when there is no occupant.

TRW decided to use ultrasonic sensors because of its robustness after a research on various occupant sensing devices [11]. The ultrasonic sensors capture a picture of the vehicle interior using sound waves. The sensing system transmits high-frequency sound waves towards the occupant and measures the time taken for the sound waves to return from the occupant. The time taken by the sound wave to travel from the occupant limits the frequency at which occupant's position can be measured to about once every few milliseconds [261].

The IR sensors send a modulated light beam to the occupant and the reflected light is received by a receiver and the phases of transmitted and received modulated waves are compared to determine the distance of the occupant. The advantage of IR sensor is that the occupant's position can be determined more frequently compared to the ultrasonic sensors. However, the IR system is more expensive as it requires sophisticated optics and electronics.

The combination of ultrasonic and IR sensors into one system can overcome the shortcomings of the individual technologies. As many as 450,000 different front passenger's positions can be detected by the combination sensors. Thus, the system can prevent the airbag deployment if the occupant is too close to the dashboard or if the front occupant is a child or if the seat is unoccupied.

With the increasing number of airbag uses in the vehicles, there is an increase in the number of occupants injured or killed due to airbag deployment, particularly OOP occupants [281]. The use of occupant detection sensors determines if there is an OOP occupant in the front seat. The airbag module makes a decision whether the airbag needs to be deployed. The main objective of the airbag module should be to balance the OOP risks with the overall occupant protection performance to achieve the highest biomechanical quality [309].

The child-sensing systems now are prioritised due to the rise in the deaths of small children in crashes. The major causes of child deaths are rear-facing infant seats and unbelted children. The sensing systems will automatically deactivate the airbag, when a child occupant is detected. Autoliv's smart airbag systems can detect a reverse-facing child seat in the front seat or if a passenger is seated near to the instrument panel [305,308]. A transponder-based approach is used to deactivate the airbag, where a sensor transmits a radio signal in conjunction with the transponder for the deactivation. Similarly, the intelligent sensing system from Temic Automotive using IR sensors can detect a rear-facing child seat or an object (e.g. briefcase) in the front seat. The fuzzy logic processor calculates the contours from the sensor information and deactivates the airbag deployment system if the seat is empty or occupied by a rear-facing child seat [306].

With the increase in the number of airbags, the use of vehicle sensing systems have dramatically increased. However, the areas such as single-point crash detection, side-impact detection and occupant weight sensing still need to be improved for better performance [310]. If due to some reason, one of the airbag sensors is tripped with sufficient force, the airbag deploys. Smart airbags avoid this by the use of a variety of advanced sensors, which determine the necessity of airbag deployment. The most basic form of smart airbag can detect the child occupant in the front passenger seat simply by an embedded weight sensor. If the occupant weighs below a threshold, the airbag system will be

Figure 35. Variable volume airbag.

automatically turned off. This method known as seat occupancy detector can also be used as a seat belt warning indicator.

As the number and type of airbags are increasing, the complexity is also increasing with the use of variety of sensors. Some of the airbag sensors can determine the position of the passenger with ultrasonic sensors, which can deactivate the airbag if the passenger is too close to the dashboard. Other sensors can determine the empty seats and then prevent the airbag from deploying. Some smart airbags can modulate the force of deployment depending on the weight and position of the passenger. A new design of side-impact sensors by Siemens Automotive uses combinations of sensors and resistors, which detect changes in the air pressure. A microcontroller collects the information on pressure change and responds to the crash impact in about 4 msec [311].

Smart airbags effectively reduce the chance of serious injury to adults as well as to children (NHTSA). As smart airbags use several sensors to monitor the weight, height and position of occupants for a tailored deploy, they can save more lives compared to regular airbags with the older technology. However, smart airbags also suffer from a number of technical difficulties such as failure to deploy even if the passenger is heavy enough to warrant it and false deployments in some instances. In these situations, the car manufacturers recall the car for analysis and fixing of the problem.

Some of the recent frontal airbags are designed to inflate with variable volumes depending on the severity of the crash, system requirements as well as the occupant's size and distance from the airbag [45]. The variable volume airbags (Figure 35) use multi-stage inflators that deploy less forcefully in moderate crashes than in very severe crashes. Occupant sensing devices can determine the occupant's seating position, the occupant type (adult/child) and whether a seat belt or child restraint is in use. On the basis of these data and other crash severity information, the aggressiveness of airbag deployment is determined.

5.2. Environmental concerns

Seat belts and airbags, which are mandatory in all recent cars, add additional production steps and environmental threats. At the end of a car's life, the disposal of components of ELVs especially non-metallic parts including airbag cushions are problematic. Different classes of materials used in the airbag module need to be identified and then separated.

These processes are time consuming and expensive, which makes the recycling of non-metallic components uneconomical. Hence, many of these components go into landfill sites. Due to a number of reasons, landfill is recognised as the least attractive option. There is the possibility of formation of methane (CH_4) by the toxic chemicals entering water courses. Methane is a greenhouse gas, which increases the possibilities of uncontrollable fire, global warming and explosions.

Although the chemical hydrolysis of nylon 6,6 [312] and polyester [313] can break down the polymers into simpler chemicals (decopolymerisation), which can be used as fresh raw materials, it is not feasible commercially. The decopolymerisation of the amide linkages of nylon 6,6 is feasible both by acid- and base-catalysed hydrolysis using the chemicals, propyl or butyl alcohol, with an aqueous solution of sodium hydroxide. In addition, the ammonolysis process and a low-temperature and atmospheric pressure process [314] can be used for the decopolymerisation of nylon 6,6. The processes for decopolymerisation of polyester involve methanolysis [315,316], glycolysis [315,316], treatment with NaOH [317] and treatment with strong acids such as sulphuric (H_2SO_4) and nitric acids (HNO_3) [315].

The uncoated airbags of polyester fabric can be recycled back to polymer form for reuse in less demanding applications. For example, the shredded polyester fabric can be mixed with 30% virgin polyester polymer, melted and re-extruded into non-wovens and can be used as the foam substitute in a new seat cover. These seat covers at the end of life cycle can be shredded, melted and extruded with higher amount of virgin polyester for reuse in still lesser demanding applications. Thus, progressive recycling of polyester items needs higher amounts of virgin polyester and the applications become less demanding. Hence, the "closed loop" recycling (i.e. the recycling material in its present context is recycled back into the original material) of airbag fabrics and many of its ancillary components is not feasible [318].

In the last two decades, the plastic materials are replacing their metallic counterparts in airbag module and other car parts as they are cheaper and lighter. However, the recycling of all the plastic components is rather difficult and not economical. Then, question arises whether in the interests of technological progress to design a highly sophisticated automobile product from the point of its optimum use or from the aspect of optimum recycling of its individual parts. A reliable ecological balance must be maintained between the amount of energy that can be saved by weight reduction or by recycling the materials.

The most difficult task in plastic recycling is the proper isolation of plastic waste and sorting into the various types according to their recycle rating. There is no point in using the energy in purifying the contaminated plastic scrap because it entails the expenditure of energy and other utilities that themselves require to be protected, e.g. air and water. Hence, fresh problems will arise from the solution itself, as additional energy must be expended in purifying the polluted air and water. In addition, some of the old components made 10–15 years ago may contain substances which are now considered as toxic, hence cannot be recycled. The use of adhesives, paints, coatings and fasteeners along with the plastics makes the recycling process further complicated.

The coated airbags are more difficult to recycle than the uncoated airbags as it is hard to separate the coating layer. Hence, they are shredded and used as landfill with some other components. The shredding produces undesired gaseous emissions and consumes energy and other resources as listed in Table 13 and 14.

In addition, the landfill can create toxic materials and heavy metals that can pollute the ground water, which in turn contaminates rivers and even drinking water.

Table 13. Amount of gas emission to air during shredding of 10 end-of-life airbag modules of a car.

Substance	Total (in g)
CO_2	1872.1
CO	8.9
HC	2.2
NO_x	10.5
SO_2	4.1
CH_4	1.9
Particulates	3.2

As the world is becoming more environmental conscious, it is appropriate that all the auto components including airbag systems are recyclable. Currently, the cost of dismantling, sorting and transporting the components of an ELV is not commercially viable. Hence, some organisations are focusing on easier recycling of the ELVs. The Association des Constructeurs Europeens d'Automobiles (ACEA) and The Recycling Consortium (TRC) are facilitating research to use recyclable materials and to design vehicles for ease of disassembly. The European Union (EU) has suggested to the OEMs to code the car parts and to produce dismantling manuals.

Some of the airbags such as the chemically grafted airbags (Reevair®) were produced with the aim of recycling. However, commercially they are not yet successful. Although, recycling of some materials is being done, there is still a long way to go. This can be attributed to the additional cost involved in the recycling of the airbags. The recycling of the airbags also emits the greenhouse gases and consumes electricity and other natural resources (see Table 13 and 14). The replacement of some of the components such as coated airbags with uncoated ones, and polyurethane foam with polyester non-woven fibre can reduce the environmental load and facilitate recycling.

The manufacturing process of airbags, especially the wet processing pollutes water. The toxic effluents released directly to the rivers are harmful to aquatic life as well as to humans. Due to the action of dissolved oxygen in the water, the pollutants are broken down chemically and biologically. Hence, the amount of dissolved oxygen in the water is reduced creating difficulties for the survival of aquatic life. The measurement of biological oxygen demand and chemical oxygen demand can provide the degree of water pollution.

Now the demand is to develop eco-friendly products from materials derived from sources other than petroleum. The dominant materials for airbags, i.e. polyamides, are mainly produced from petroleum resources, which is a limited resource and cause global

Table 14. Total consumption of power during shredding of 10 end-of-life airbag modules of a car.

Source	Total (in MJ)
Electricity	1.78
Crude oil	19.35
Hard coal	3.78
Natural gas	1.27

warming. The biomass plastic such as aliphatic polyester is the alternative for this. However, biomass plastics are inferior to polyamides in strength, heat resistance, impact resistance and hydrolysis resistance. Fukudome et al. [319] used PA 5,6 filaments with higher strength and lower elastic modulus compared to PA 6,6 for the airbag fabrics. They achieved the desired properties by boiling water treatment and heat shrinkage. These fabrics are considered eco-friendly as they contain PA 5,6 as a biomass plastic material. The study revealed that specific treatment of PA 5,6 can perform better than PA 6,6, and can be an alternative material for PA 6,6.

The current trend is towards using fewer fibre types, recyclable materials and less chemical finishing or even uncoated airbags to make the recycling easier. The environmentalists' watch words "reduce, reuse and recycle" should be used in the automobile industry. Although the attitudes of companies are changing towards "green" cars, action by government is necessary in many cases to ensure certain processes are carried out. Approved legislation is necessary for OEMs to make them responsible for disposing of all ELVs at no cost to the last owner. The use of cars is increasing both in developing and developed countries which produce more pollution as summarised by the equation:

$$\text{Impact on environment} = \text{Population} \times \text{Affluence} \times \text{Technology}.$$

As all the three dependent factors are increasing at an alarming rate, environmental disaster is inevitable without strict regulations. Although some earlier environmental laws exist, they need to be modified as the quality of life changes with the time. The leaders in the world community such as EU, United Nations and ISO are implementing new legislation in addition to the legislation by local government. The ISO 14000 series is a group of voluntary international standards, which provide consistent and effective environmental management system for all operational procedures. ISO 4001 is a family of standards, which cover all issues from environmental auditing to the assessment of life cycle of products. In addition, the automobile producers and the airbag manufacturers should consider the environmental-, health- and safety-related issues seriously. All major manufacturers should formulate effective environmental policies and environmental management systems.

5.3. Future trends

The future of airbags is promising, as there are a wide range of applications ranging from motorcycle helmets to aircraft seating. The airbags in future will be more economical, due to the developments in the technology and availability of advanced materials. The focus of the airbags from the very early stages of development is longer service life, smaller package size, cost reduction and improved occupant safety. Due to the sharp increases in the prices of new automobiles, car owners try to keep their vehicles longer before trading them in. As per the legislation, the legal ramifications of failed safety devices can be ruinous. Hence, the safety restraint systems should perform longer even under more adverse conditions.

The airbags in most recent cars use and in future will be using a range of intelligent sensing elements to ensure the severity of a crash before the deployment. This reduces the likelihood of airbags deploying in the case of minor crashes. Table 15 compares the requirements of airbags in the past, present and the future.

The first generation airbags were of larger size. The design of smaller cars provided lower amount of interior space to accommodate these airbags. However, the technological

Table 15. Airbag system past, present and future.

Devices	Past	Present	Future
Airbags			
Driver side	X	X	X
Passenger side		X	X
Rear seat			X
Side-impact		X	X
Head protection			X
Knee bolsters			X
Inflators			
Pyrotechnic	X	X	X
Compressed gas			X
Hybrid			X
Dual chamber			X
Variable rate			
Sensors			
Mechanical accelerometer	X	X	X
Electronic accelerometer		X	X
Dual-threshold crash sensor			X
OOP			X
Rear-facing child seat			X
Weight sensor			X
Seat occupancy			X
Inflator pressure and temperature sensor			X
Systems			
Single-point sensing		X	X
Distributed sensing			X
Centralised squib firing		X	X
Distributed squib firing			X
Seat belt pre-tensioners		X	X

developments superimposed with the size reduction favoured to achieve the same level of protection, which was hard to achieve. It is an established fact that certain airbag deployments cause injuries such as bruises, abrasions, scratches, contusions and burns. However, the modern airbags are designed with lighter, softer and smoother fabrics with lower surface friction to reduce bruises and abrasions. The main focus is then to reduce the secondary injury risks, while improving the primary injury protection.

The airbag triggering algorithms used in recent vehicles are becoming much more precise and complex. They try to reduce unnecessary deployments and to adapt the deployment speed to the crash conditions. The algorithms are considered valuable intellectual property. Experimental algorithms may take into account such factors as the weight of the occupant, the seat location, seat belt use, and even attempt to determine if a baby seat is present. In future airbags, fuzzy logic controllers should be used to address the complexity of the restraint system. The system should include occupant detection sensors, weight sensors both for driver and passenger, a distributed crash sensor arrangement, a dual-stage airbag for both the driver and passenger and a microcontroller implementing a fuzzy logic algorithm [71].

Crash sensors can be fitted in several positions on the front and rear of the vehicle, which can monitor the airbag deployment. The future airbags will be smaller and lighter in weight, with more integrated systems and improved sensors. Tomorrow's airbag systems will be smart adaptive restraint system that can detect the size and position of the occupant, OOP conditions, distance between the occupant and the airbag module as well as the severity of the crash [71]. Depending on these conditions, the airbag deployment (i.e. the height and velocity) can be tailored or the airbag can be completely disabled. The future airbags will be focusing on the following parameters:

- Lighter fabrics with good packability and use of cold inflator technology.
- New coating polymers.
- New advanced application of airbags such as side curtain, rollover protection, external pedestrian protection and other special areas.
- Consolidation/integration of supply chain.
- Combinations of non-wovens and film.

Newer designs of airbags need to hold the air for longer times with reduced levels of coating material. Hence, the coating should provide effective air retention as well as prevent edge combing in order to sufficiently protect the driver or the passenger. The new airbag designs will be more sophisticated with a wide range of advanced technologies.

6. Conclusion

The airbags are essential safety devices, well known for their technical efficiency in saving lives and minimising injury to drivers and passengers involved in automobile collisions. Airbags are known as supplemental restraint systems, as they supplement the protection offered by a vehicle's construction and by seat belts. During the airbag deployment, especially in side impacts, rear impacts and rollovers, seat belts are essential to hold the occupant securely in place. The effectiveness of combined airbags and seat belts in saving injuries and fatalities has been proven to be higher than seat belts and much higher than airbags alone.

The airbag industry has experienced tremendous growth in the last two decades due to strict legislations combined with better driver education and safety awareness. The number of airbags has tremendously increased from one or two (first generation airbags) to five or more in most of the recent car designs. Similarly, the heavy and bulky airbags of the past are now being replaced with lighter and smaller airbag designs. The airbag system of today is a passive supplemental restraint that is used to cushion the occupant during collisions. The airbag system of tomorrow will be a smart adaptive restraint system consisting of sensors, actuators and protective devices, which will help in tailoring the deployment of the airbag according to the prevailing occupant conditions. The smart restraint system will detect much about the occupants by employing sensors and will work genuinely in saving lives.

When airbags were first introduced, their primary objective was to save the occupants of a car or similar passenger vehicle in frontal collisions. The modern cars are fitted with several other airbags to protect from rear and side impacts and rollovers. Hence, various types of airbags such as side-impact airbags, centre airbags, curtain airbags and knee airbags are being used in almost all the modern cars. Furthermore, the first-stage airbags were only used in passenger cars and other automobiles. There are several other applications of airbag technology in various fields such as military, aerospace, motorcycle and pedestrian protection.

Although airbags save lives in a crash, there are many cases of minor to severe injuries of the occupants due to their deployment. Minor injuries to the face, neck and upper limbs are the common incident, whereas severe or fatal injuries can occur when airbags deploy due to the occupants' proximity to the airbag, OOP or in direct contact. Improvements in sensing, propellant type, airbag designs and technology of deployment can avoid these injuries. Hence, the research on airbags should primarily focus on reducing the airbag-induced injuries and improving airbag's effectiveness in saving lives.

It is mandatory in many parts of the world that all the cars should be equipped with safety devices such as airbags and seat belts. However, the production of airbags adds additional production steps, extra cost and environmental threats. At the end of a car's life, the disposal of the components of an airbag module is rather difficult and creates environmental problem. The recycling process of non-metallic components of an airbag module is time consuming and expensive, which is still not adopted by many car manufacturers. Hence, many of these non-metallic components go into landfill sites. Due to a number of reasons, landfill is recognised as the least attractive option leading to the possibility of emission of the greenhouse gases, methane and toxic chemicals entering water courses. Some future research should focus on the easy recyclability of airbags to meet demanding environmental specifications.

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List of abbreviations

ACEA	Association des Constructeurs Europeens d'Automobiles
ACRS	air cushion restraint system
CAS	cockpit airbag system
CFM	cubic feet per minute
CRE	constant rate of elongation
CV	coefficient of variation
ECSU	electronic crash sensor unit

ECU	electronic control unit
ELV	end of life of a vehicle
EU	European Union
Euro NCAP	European New Car Assessment Program
FMVSS	Federal Motors Vehicle Safety Standards
FE	finite element
GM	General Motors
IPN	interpenetrating network
IR	infrared
ITS	inflatable tubular structure
MEMS	microelectromechanical system
NASA	National Aeronautics and Space Administration
NHTSA	National Highway Traffic Safety Administration
OEM	original equipment manufacturer
OOP	out-of-position
OPW	one piece woven
OWM	open weave material
PA	polyamide
SRS	supplemental restraint system
TEA	Transportation Equity Act
TRC	The Recycling Consortium
TRL	Transport ResearchLaboratory
UN	United Nations
UNECE	United Nations Economic Commission for Europe

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