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REAL-WORLD COLLISION EXPERIENCE FOR AIRBAG TECHNOLOGY

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ABSTRACT

Airbag systems are now commonly installed in the Canadian motor vehicle fleet. This situation is likely to continue in the immediate future as manufacturers comply with American legislation requiring airbag fitment in all light duty vehicles by 1998. However, there are major differences between the collision involved populations of the United States and Canada, primarily in respect of the disparity in the usage rates for seat belts in the two countries. This fact has significant implications on the overall benefits likely to be achieved in Canada with current airbag systems. Issues of concern include the introduction of new injury mechanisms as a direct result of airbag deployment; an increased risk of occupant injury at low collision severities; and the added societal costs associated with airbag systems when deployed unnecessarily. These issues are discussed in the light of data obtained from real-world airbag deployment crashes, and automotive engineering trends which are likely to result in substantially different implementations of this technology in the future.

1. INTRODUCTION

Airbags are not a new phenomenon, having been installed in a test fleet in the early seventies [1]. Initially viewed as a means of providing passive occupant protection, manufacturers today describe airbags as supplemental restraint systems. Thus, airbags are seen primarily as a means of increasing the protection offered by lap and shoulder belts.

Both belted and unbelted occupants might be expected to benefit from airbag deployment in high severity events. Over a range of low collision severities, a driver who is properly restrained by the available lap and torso seat belt system would not be expected to require the supplemental protection offered by an airbag. However, their unbelted counterparts may benefit from the deployment of the relatively-large airbag. The situation is further complicated by such factors as the differences in the anthropometry of individuals, and the consequent wide variations in their seating geometry. Similarly, occupants of different ages exhibit substantial variations in injury tolerance. Thus, the challenge for the occupant restraint designer is to offer effective protection to these different individuals over the entire spectrum of collisions.

It must also be recognized that airbags are pyrotechnic devices which add energy into what can already be a high energy event. Consequently, there is an associated risk of injury from the deploying bag. Furthermore, airbag deployments can be expected to introduce a variety of new injury mechanisms [2]. Thus, in evaluating the overall safety benefit of airbag systems, one must carefully examine the level of risk reduction afforded by the airbag against certain injury mechanisms and the added risk of airbag-induced injury.

2. CURRENT AIRBAG TECHNOLOGY

Airbag systems designed to provide frontal impact protection are sensitive to longitudinal components of vehicle deceleration. The crash sensing and deployment control system is usually either electro-mechanical or fully electronic, while a pyrotechnic inflator is used to deploy the airbag [3].

Although the actual criteria for deployment are dependent on the specific make and model of a given vehicle, deployment will normally occur in crashes where the equivalent barrier speed exceeds 15-25 km/h [4]. Sensing systems must be capable of discriminating between crash pulses across widely differing collision types and severities [5]. For example, one would wish the airbag to fire in a moderately severe head on crash, but not to deploy should the vehicle travel over a section of rough road. In practice unwarranted deployments are infrequent, but these do occur.

In electro-mechanical systems, crash sensing is typically realized using a safing (or arming) sensor, and either two or three discriminating sensors. Each type of sensor features a mass which is constrained to move along the vehicle's longitudinal axis [6]. In the ball-in-tube type of sensor, a magnet provides a bias force on a steel ball. An alternative type has a roller, biased by means of a spring. In both cases the mass moves forward in response to a sufficiently large deceleration and closes an electrical circuit. The safing sensor has the lower bias force and is generally housed within the airbag control module located in the vehicle's interior. The discriminating sensors are distributed across the front end of the vehicle; these are electrically connected in parallel to each other, and in series with the safing sensor. Thus, the safing sensor and at least one discriminating sensor must close for the airbag to be deployed.

Fully-electronic sensing and control systems are becoming increasingly common. These utilize solid state accelerometers and micro-processors combined in single-point sensing units. Sophisticated algorithms analyze the crash pulse and distinguish deployment and non-deployment events. These systems are extremely flexible since the desired response can be readily adjusted solely by modification of the control software. For example, inputs from seat belt use sensors can be used to permit variable deployment thresholds.

The inflation module contains both the airbag and the pyrotechic inflator. The aluminum casing contains an igniter (squib), fuel pellets, and a diffuser. The combustion of the sodium azide fuel produces mainly nitrogen gas which is filtered to remove residual particulates. The gas inflates the airbag, and is exhausted through vents in the fabric into the occupant compartment. Some particulates, including small amounts of sodium hydroxide, may be released as a fine aerosol. While sodium hydroxide is a strong alkali, it quickly converts to non-toxic sodium carbonate [7].

Most airbags are made of nylon due to its strength, abrasion-resistance, aging-properties, and superior performance over a wide range of environmental conditions. A neoprene coating may be used on the inside of the bag to help control the exhaust gas flow. The airbag is packed into the module, like a parachute, in one of several different folding patterns. A plastic cover trims out the surface of the inflation module. These covers are designed to tear easily along scored lines during airbag deployment; however, they must be sufficiently robust to remain intact for the life of the vehicle.

The inflation characteristics are governed by the gas output of the inflator, the tear pattern of the cover, the fold pattern of the airbag, and the venting system. The greatest effect is produced by the inflator design. Deployment is very rapid, with peak speeds for the leading edge of the airbag measuring in the range of 170-340 km/h [8]. In order to further control deployment characteristics internal tether straps are sometimes used to reduce airbag excursion, and to modify the ultimate shape.

On deployment, the driver's airbag forms an essentially circular cushion, holding about 60 litres of gas. Passenger bags produce a tear-drop shape of two or three times this volume. The driver's module is a bolt-on unit on the steering wheel, while the passenger unit is integrated into the dashboard.

Bag deflation is controlled by the number, size, and location of vent holes in the bag. Typically such vents are located in the rear of the bag so as to direct the hot exhaust gases away from the occupant. Rather than using vents, some designs increase the porosity of the bag fabric in specific locations.

The timing of airbag deployment must be carefully managed for the bag to provide a cushion as it is impacted by the occupant. In a frontal barrier collision, maximum engagement occurs within about 100 ms. Crash sensing is accomplished in the first 20 ms of the crash pulse, and the airbag is fully inflated within 50 to 70 ms of initial contact.

The deployment sequence is initiated by the crash sensors detecting the vehicle's deceleration. The control module determines that airbag deployment is warranted and produces an electrical signal to the squib which ignites in about 1 ms. This initiates combustion of the sodium azide fuel pellets which generates gas. Gas pressure rises rapidly which results in the airbag bursting through the module cover. The gas expands, inflating the airbag which is fully deployed in 40-50 ms. The occupant contacts the fully inflated air bag and rides it down as gas is forced through the bag's vents. The bag is fully deflated in 1 to 2 s.

3. FIELD ACCIDENT EXPERIENCE

In order to address the safety issues surrounding airbag technology, Transport Canada has been conducting research into real world motor vehicle collisions involving air bag deployments for the past two years [9]. Specialized research teams located in engineering faculties at a number of universities across Canada are involved in this work. To date, over 400 crashes have been investigated in detail.

Results from this research programme, including individual case studies of collisions investigated by the team at the University of Western Ontario, are presented below. The emphasis for each case is on the collision severity, the crashworthiness of the airbag equipped vehicle, and the mechanisms of injury to its occupants. A Collision Deformation Classification, CDC, [10] is used to describe the damage resulting from the major impact to the case vehicle. The equivalent barrier speed, EBS, associated with the vehicle damage is computed using SLAM [11]. The severity of occupant injuries is described using the Abbreviated Injury Scale, AIS [12]; the overall severity for any given occupant being denoted by the maximum AIS, MAIS.

3.1 Moderate and severe frontal impacts

In moderate to severe frontal collisions, airbag systems, used in conjunction with seat belts, do substantially reduce occupant injury, especially trauma to the head and face:

ACRS-1616: A 1990 Lincoln Mark VII was travelling along the curb lane of an urban arterial at high speed when it sideswiped another vehicle travelling in the passing lane. The Lincoln egressed from the right side of the roadway and ran onto an automobile dealer's lot where it struck a 1994 Dodge Ram D-350 Pickup Truck, the first in a line of parked vehicles. Damage at the level of the front bumper of the Lincoln was moderate with considerable override (CDC=12FDEW3); the EBS was estimated at 38 km/h. The driver was a fully restrained, 30-year-old male. His airbag deployed in the crash and he sustained only a minor abrasion to the right forehead (MAIS 1). The right-front passenger, a 32-year-old, male, was fully restrained but had no airbag available. He received a contusion to the right side of the head from contact with the side window (MAIS 1).

Whereas airbags are effective in mitigating against head and face injuries in moderate to severe frontal crashes, they may not reduce the frequency and severity of lower extremity injuries. This is readily demonstrated by the following case study:

ASFS-0846: A 1990 Chrysler Diplomat was involved in a high-severity frontal impact with a 1989 Chevrolet van. The Diplomat sustained broad crush, to a maximum extent of 104 cm, as measured at the right bumper (CDC=12FZEW5). The EBS was estimated to be 70 km/h. The fully restrained, 52-year-old, male driver survived this collision with no head or chest injuries due to supplemental airbag protection. His injuries comprised a fractured right ankle, multiple bruises, and abrasions (MAIS 2).

It must also be noted that airbags are not a panacea for all types of crashes and for all crash severities. In particular, some impacts are of such high severity, or result in such extensive structural intrusion into the occupant compartment that, regardless of seat belt use or airbag deployment, they remain unsurvivable. The following case is an example of such a crash:

ACRS-1648: The alcohol-impaired driver of a 1994 Chevrolet Astro Van allowed his vehicle to cross the roadway centreline and to travel into the path of a 1985 Dodge Ram flatbed truck loaded with gravel. Both vehicles were travelling at highway speeds. The deck of the flatbed, extending outboard of the left side of the cab, engaged the extreme left front end of the Astro Van. The truck raked down the left side of the van (CDC=12FLAA9). The 27-year-old male driver of the van was unbelted. His airbag deployed in the crash, but as a result of the collision configuration, there was extensive intrusion into the occupant compartment and he sustained fatal injuries to the head and chest, and traumatic amputation of both lower legs (MAIS 6).

3.2 Low severity frontal impacts

A preliminary analysis of Canadian data has indicated that that the deployment threshold for current airbag systems is set at an exceptionally low level [13]. In fact, most airbag deployment crashes occur at or near the threshold for deployment. We must also recognize that seat belt usage rates of the order of 90% are the norm for Canadians, and that, in such low severity collisions, the use of seat belts provides adequate occupant protection. Thus, in minor crashes, the deployment of an air bag is at best redundant, and at worst can result in restrained occupants sustaining airbag induced injuries [14].

In particular, minor injuries to the face and upper extremities are common as a result of direct contact by the deploying airbag fabric, the so-called phenomenon of "bag slap". The following case study is but one example of an exceedingly low severity crash resulting in minor airbag-induced injuries:

ASFS-1641: The 24-year-old, fully-restrained, female driver of a 1994 Plymouth Sundance travelled through a narrow entrance way between two buildings. She slowed her vehicle and made a tight 90-degree turn into a parking space. The right front end of the Sundance contacted a concrete wall. The only residual damage to the car was a series of abrasions to the surface of the front bumper (CDC=12FRLN1). The impact speed was estimated to be under 10 km/h. The driver's airbag deployed and struck her underneath the chin, resulting in a 5 cm x 5 cm abrasion accompanied by minor swelling.

While most such trauma is of a minor nature, occasionally more serious injuries are found to occur. One specific area of concern is the occurrence of fractures to the upper extremities [15]. The latter injuries may occur as a result of interaction of the airbag, the driver's hand, and the steering wheel system; or by direct contact by the airbag module's cover during deployment. Fractures to the arms may also result indirectly by the deploying airbag causing the arms to flail and strike portions of the vehicle interior. An example of upper extremity fractures resulting from a minor collision is provided below:

ACRS-1601: A 1993 Dodge Caravan was travelling on an urban roadway when a 1989 Chevrolet Blazer coming from the opposite direction made a left turn in front of the van. The front end of the Caravan struck the right side of the Blazer. This was a minor impact (CDC=11FDEW1) with little risk of injury for the van's occupant. In this case, the fully-restrained, 57-year-old, male driver braced against the steering wheel prior to impact. He sustained fractures of the fifth metacarpals on both hands, and facial abrasions, all as a result of interaction with the airbag.

3.3 Unusual injury mechanisms

The pyrotechnic nature of current airbag systems also results in some adverse effects. Localized burns may occur as a result of direct exposure of the skin to hot exhaust gases. Such incidents are infrequent, and the majority of "burns" reported as resulting from airbag deployments, are actually found to be abrasions due to bag slap. The products of combustion of the airbag propellant, while largely benign, may include small quantities of sodium hydroxide. Chemical burns arising from such a source are rare; however, incidents of alkaline eye injury are of particular concern as these can result in visual impairment [16]. The authors at The University of Western Ontario, in conjunction with their medical colleagues, have conducted an in-depth collision investigation and clinical case history of one such occurrence [17], a brief synopsis of which is presented below:

ASFS-1629: A 1992 Lincoln Town Car was involved in a high-severity, offset-frontal impact with a 1991 Chrysler Dynasty. There was over 1 m of crush to the left front end of the Lincoln, with substantial occupant compartment intrusion to the dashboard and floor on the driver's side (CDC=12FLEW4). The EBS was estimated to be 50 km/h. The fully-restrained, 52-year-old, female driver sustained fractures to the left forearm, left femur, right tibia, right fibula, and left foot. She also exhibited significantly increased levels of pH in both eyes and, despite aggressive management, the left eye suffered a loss of visual acuity.

Contact by the air bag to the head and face normally results in only minor to moderate injuries; however, there is potential for more serious trauma. For example, should significant hyperextension of the neck occur, there is a possibility of cervical spine fracture [18]. Adverse interactions of airbags with eyeglasses, and a tobacco pipe, have been reported to result in serious injuries [19,20].

The potentially injurious effects from interactions with airbag systems may well be exacerbated for occupants who are located in close proximity to the airbag module at deployment. This can pose a serious hazard for occupants who are significantly out of position at the instant of deployment. For example, a driver may slump forward over the steering wheel as a result of falling asleep, or due to a medical problem. Such an occupant will then be effectively in direct contact with the airbag module.

ASFS-1633: An unrestrained, 74-year-old, male driver of a 1994 Saturn SL1 was observed to be slumped over the steering wheel prior to impact with the side of a municipal transit bus. Damage to the car at bumper level was minimal; however, there was considerable override (CDC=12FDAA6). The driver sustained bilateral rib fractures as a result of thoracic loading from the airbag, and a severe closed head injury from contact with the windshield header. He was found to be dead at the scene. The post-mortem examination revealed that the occupant had suffered a heart attack prior to the crash.

Significant airbag loading can also occur to occupants who, as a result of their small stature, require being seated closer than normal to the airbag module. Another specific concern is the potential for interaction between an airbag and a rear-facing infant carrier located in the right-front seat [21].

4. SYSTEM COSTS

While the cost of front airbag systems as original equipment is in the order of hundreds of dollars, the cost of replacement can be significantly higher. In a sample of cases investigated by the authors, the costs of replacement airbag modules ranged from $500 to $1500 for the driver's system, while passenger units varied between $1000 to $2000.

There are also additional costs related to other component parts and labour. For example, manufacturers may require replacement of sensors and/or control units following deployment. Also, repair of airbag-related damage is not necessarily confined to the airbag system itself. Passenger airbags often break the windshield and damage the dashboard, necessitating replacement of these components. As a result, repair costs associated with the passenger's airbag are often significantly greater than those for the driver's system.

Such high repair costs are of particular concern in Canada, where most occupants are restrained, and the low deployment threshold exhibited by current systems results in questionable safety benefits. The situation is compounded by the low occupancy rate in the right-front seating position. In our study there were 95 deployments of passenger air bags; however, there were only 36 passengers present, showing an occupancy rate of 38%.

How the cost of airbag system repairs will be reflected in future automobile insurance premiums remains to be seen. Most deployments are at low crash severity, and many of these vehicles are repaired and the airbags replaced. However, the high costs associated with such replacement can increase the overall vehicle repair cost to the point where this is no longer economical, and the vehicle becomes a total loss. With a number of provinces in Canada having public insurance schemes, there is a need for detailed analysis of cost data associated with airbags.

5. FUTURE AIRBAG TECHNOLOGY

Airbag systems have evolved over two decades, and the diverse nature of current research on these systems indicates that the technology will continue to be developed. Field experience with current airbags suggests that enhancements to this technology are certainly needed. While present systems offer a degree of passive protection to the unrestrained, their aggressive nature does compromise the overall safety of belted occupants. This is of particular concern given the relatively low crash severity threshold for airbag deployment. The situation is exacerbated for occupants who may be positioned in close proximity to the deploying airbag.

These issues are of great concern in Canada, where seat belt use is the norm. However, whereas seat belt usage in the United States currently lags considerably behind that in Canada, there is a general trend for increasing use in that country. Most states now have mandatory usage laws, and a number of states are aggressively pursuing education and enforcement programmes. Thus, Canada today, may well provide a benchmark for the situation which may develop in the United States over a five to ten year time frame. Given the relatively long lead times for design, development, and implementation which are required by the automotive industry, airbag systems developed in north America over the next few years may well be required to protect a significantly different occupant population than exists today. This proposition is worthy of careful consideration as it is certain that airbag systems tuned to provide protection to the unrestrained, are considerably different from those optimized for fully-restrained occupants [22].

However, even if it is determined that passive protection of unbelted occupants remains a major goal, consideration must also be given to improving the collision performance of airbags for the restrained population. Future developments in the technology may well provide innovative solutions which will enable the specific needs of both types of vehicle occupant to be addressed.

In general, current research and development activities are centered on producing "intelligent" occupant restraint systems. "Smart" airbags will likely be able to sense whether or not an occupant is using the available seat belt; if an occupant is in fact occupying a given seat; and the position of such an occupant with respect to the airbag module. Modifications to seat belt systems such as the addition of pretensioners, webbing clamps, and load limiters may also be adopted [23]. The combination of some of these ideas will allow both seat belts and airbag systems to be tailored to the needs of the occupant to be protected in a specific crash.

In fact, an airbag system incorporating seat belt usage detection to modify the deployment characteristics is currently in production. The system used by Mercedes-Benz incorporates seat belt sensors. The algorithm used to fire the airbag takes into account the occupant's seat belt use and provides for dual-threshold deployment. If, for example, a driver is unrestrained, the system allows the airbag to fire at a particular level of crash severity. However, should the driver be belted, the airbag will not fire until a second, higher crash severity is detected. Thus, this system provides a degree of passive protection to unrestrained occupants at low collision severity, while truly functioning in the role of a supplemental restraint for belted occupants in more severe crashes.

A second method of mitigating against airbag induced injuries is to modify the characteristics of the inflation module [24]. Initially, the proposal is to have a two-stage inflator where the airbag's inflation rate, and the unit's gas output, would be varied in two stages as a function of collision severity. When a baseline collision severity is detected the airbag is triggered with the inflator operating in single stage mode. In more severe crashes, second stage inflation would occur simultaneously to boost the deployment. Triggering only the first-stage deployment in low severity incidents is intended to reduce deployment forces, provide a softer airbag system, and hence to reduce the injury potential associated with the deployment of the airbag.

Many manufacturers either already have, or are planning to implement, all electronic crash sensors for their airbag systems. Two-stage inflators appear to be some time away from being available as a production item, and thus it seems likely that dual-threshold deployment systems based on seat belt usage may be generally adopted in the first instance. Such airbags, while retaining their current aggressive deployment characteristics, would provide significant benefits to belted occupants by not deploying in minor collision events.

The costs associated with airbags as original equipment, and especially in terms of the need for system replacement following a crash, are not insignificant. Consequently, the designer needs to take account of the utility in deploying one or more airbags in a crash. However, to avoid such unnecessary deployments requires sophisticated sensing and control systems. For example, the sensors must be able to detect the presence of an object in the right front seat, while discriminating between a bag of groceries placed there, and a human occupant. Research is currently in progress on a number of occupant sensing systems, based on some form of weight and/or volume detection [25]. One such system has been implemented by BMW [26].

A specific requirement for occupant sensing is the detection of a rearward-facing infant carrier located in the right front seat. In such a case, the back of the child restraint would be in close proximity to the passenger's airbag inflation module with the potential for significant loading to the child restraint should the airbag deploy. Currently manufacturers provide warnings against such usage. Furthermore, a safety regulation has been proposed which would require a manual cutoff switch for the passenger's airbag in two-seat vehicles, where a child restraint cannot be installed in the rear seat. In fact, one pickup truck manufacturer has already provided such capability [27]. Nevertheless, the potential for inappropriate use of an infant carrier in an airbag equipped seating position exists and automatic switching mechanisms are being developed [28].

An associated problem is that of the occupant who is in extremely close proximity to the airbag module at the time of a crash. Work is being conducted on occupant position sensing systems, primarily using either ultrasonic or infra-red range finders [29]. The development of such sensors may provide a means to warn an occupant of inappropriate seating geometry. Alternatively, if such sensors were to be combined with multi-stage inflators, it might be possible to limit occupant exposure to deployment forces.

Another technological change likely to occur is the type of propellant used to inflate airbags. Airbag suppliers are now developing non-azide propellants, and hybrid systems which use argon gas stored under pressure, with a small amount of propellant to augment inflator output [30].

Whereas this paper has focused on airbags designed to offer occupant protection in frontal collisions, systems are being developed for use in side impacts. Volvo have such an airbag in production as part of their side impact protection system [31]. The airbag is located in the outboard seat back, the sensor being an electro-mechanical switch mounted on the seat's frame. The bag has a volume of about 12 litres and provides a cushion for the occupant's thorax. Other manufacturers are developing similar door-mounted bags [32], while BMW also has an airbag which deploys from the roof side rail to offer a degree of head protection [33].

6. CONCLUSION

Although airbags are marketed as supplemental restraints, designed to provide additional protection to that offered by the use of seat belts, current systems are designed primarily to provide passive protection to the unrestrained.

Field experience in Canada has shown that, whereas airbags do offer good head protection to belted occupants in severe frontal crashes, at lower collision severities they frequently expose belted occupants to airbag-induced injuries. Such injuries are often sustained at crash severities where a belted occupant normally escapes without any injury. Not all such injuries are necessarily minor in severity. Under certain situational factors, deployment of an air bag can expose belted occupants to severe or even potentially fatal injuries in collisions of very minor severity.

Potential enhancements to this technology are likely to provide better future safety performance. The adoption of dual threshold deployment systems based on occupant seat belt use, and occupant presence sensing, will lead to airbags deploying only when necessary. Future systems may further customize airbag deployment to a specific individual in a specific crash. Such changes to airbag technology are likely to provide both safety and cost benefits.

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