Air Bag Induced Fatalities in Canada

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Abstract

The past decade has seen the widespread introduction of air bags in the Canadian fleet; however, the collision performance of these systems, as supplements to seat belts, has been mixed. In severe crashes, air bags have provided good head protection, whereas in low severity collisions, the energy of the deploying air bag has often been the dominant factor in injury production. This has been especially notable in a number of minor crashes where vehicle occupants have been fatally injured, with the injury mechanism being attributed to adverse interaction with a deploying air bag. Based on the experience from in-depth investigations of real-world collisions, and an intensive crash test programme, a variety of countermeasures have been developed. While these have had a very positive effect, concerns remain over the level of public knowledge of air bag safety and, in particular, the precautions being taken by individuals who are at greatest risk. The current paper reviews a series of low severity crashes involving air bag induced fatalities that have been researched in detail. The resulting implications for the design and testing of future safety systems, their regulation, and the dissemination of relevant information to vehicle users are discussed.

Résumé

Au cours de la dernière décennie, le coussin gonflable s'est répandu à l'ensemble des véhicules au Canada. Cependant, l'efficacité de ce système de protection supplémentaire avec celle des ceintures de sécurité, n'a pas été constante. Lors de collisions sévères, le coussin gonflable a offert une bonne protection à la tête, tandis que son déploiement lors de collisions mineures a souvent été la principale cause de blessures. Ce fait a particulièrement été remarqué dans un certain nombre de collisions mineures où les occupants des véhicules ont subi des blessures mortelles causées par le déploiement de coussin gonflable lui-même. On a développé une variété de contre-mesures à l'aide des enquêtes approfondies suivant des collisions réelles et d'un programme intensif d'essais de collision. Bien que ces contre-mesures ont eu un effet très positif, on s'inquiète toujours de la connaissance du public au sujet de la sécurité du coussin gonflable et, plus particulièrement, des précautions prises par les personnes les plus à risque. Le présent document décrit une série de collisions mineures où le coussin gonflable a causé des blessures mortelles qui ont fait l'objet d'enquêtes approfondies. Les implications qui en résultent en matière de conception et de test des futurs systèmes de sécurité, les règlements connexes et la diffusion de l'information importante parmi les usagers de la route sont discutés.

Introduction

During the past decade, the provision of air bags as supplements to lap-shoulder belt systems in the front outboard seating positions of light duty vehicles has become commonplace. These air bags have been found to provide additional benefits to belted occupants, particularly in severe frontal collisions. However, instances of air bag induced injuries, especially fatal injuries in extremely low severity crashes, have also been noted.

Potential difficulties in protecting unrestrained adults by means of air bags, while accommodating the likelihood of out-of-position occupants, especially children in passenger seating positions equipped with such systems, were identified in early research and development programmes [1]. With the widespread introduction of air bags, the actual field injury experience has been similar in both Canada and the United States which is not surprising given that, in general, the same makes and models of vehicles are sold in both countries. Nevertheless, the U.S. has witnessed a proportionately greater number of air bag induced fatalities than Canada. The main reason for this discrepancy appears to be greater seat belt and child restraint use in our country.

In the U.S., the National Highway Traffic Safety Administration (NHTSA) has been compiling statistics on fatalities and serious injuries resulting from air bag deployment crashes since 1990. Up to the end of 2002, a total of 227 individuals in the U.S. are reported to have been killed in this manner. [2] The range of fatal injuries resulting from adverse occupant-air bag interactions, and specific details of the associated biomechanics, have been documented in a recent publication. [3]

Of the total number of U.S. fatalities, there were 76 drivers plus 10 adult and 141 child passengers. Most of the 86 adults were either unbelted (55) or misusing seat belt systems in some manner (5). The belt use for two drivers was not known. Nevertheless, 21 drivers and 3 right-front adult passengers, 28% of the adult occupants, were fully restrained at the time of the crash. The proportion of fatally-injured children who were fully restrained at the time of their collision was dramatically less; with only 5 of the 141 children killed (less than 4%) being so belted.

Twenty two children were located in rear-facing infant carriers, placed in the right-front seat, adjacent to a passenger air bag. Ten of these infants were properly secured in the child restraint which, in turn, was anchored by the vehicle's seat belt. For the remaining 12 of these infants, in addition to being located in the front seat and adjacent to an air bag, some form of misuse of the seat belt and/or child restraint was evident. This included seat belts not being used properly to anchor the child restraint in the vehicle, and the child restraint harness not being properly used to retain the child in the child seat.

In addition to the 22 children using rear-facing infant carriers noted above, 119 other children were reported to be fatally injured as a result of air bag deployment crashes. Of this total, 92 were unrestrained, with 23 of these children sitting on the lap of a front seat occupant. The restraint status of one child was unknown. A further 21 children were improperly restrained, including using only the lap portion of a lap-torso belt, having the torso belt located beneath the arm, or sharing a belt with another occupant. Only 5 of the fatally injured children were fully restrained at the time of the crash.

For several years, Transport Canada has been actively monitoring air bag deployment crashes across the country. Special emphasis has been placed on incidents where fatal injuries have resulted to either a driver or a passenger when an air bag has deployed in a low severity collision. A number of such cases have been identified, and all have been subjected to in-depth investigation and reconstruction by experienced researchers. Many of the circumstances occurring in these real-world events have also been integrated into Transport

Canada's crash test programme in support of the development of a variety of countermeasures.

All of the low severity, air bag induced fatalities that have occurred in Canada to date are reported in this paper. Several of these incidents have been documented previously in some detail, and so only brief descriptions are provided here. The focus of this paper is on a number of recent collisions, with emphasis on the lessons learned from the investigation and reconstruction process, together with an indication of the current and future Canadian countermeasures that are designed to help avert similar tragedies in the future.

Low-Severity, Air Bag-Induced Fatalities

In the following documented situations, the fatal injury has been attributed to adverse contact between a deploying air bag system and the associated vehicle occupant in a low severity collision event.

ACRS-1103:

A 1993 Ford Probe GT two-door hatchback ran into the gore area of a Y-intersection. The front of the vehicle initially struck a metal sign post (12FCAN6), then sideswiped a large diameter pole supporting an overhead sign (11LDAW2).

Figure 1. 1993 Ford Probe

The 37-year-old, male driver was unrestrained. He sustained massive head and chest injuries that included: avulsion of the brain stem; fracture and dislocation of the odontoid process of C2; complex fracture of the basal skull; complex laceration of the spleen and right lobe of the liver; and flail chest.

The collision circumstances suggest that the driver, who was alcohol-impaired, had passed out and was slumped forward over the steering wheel when the air bag deployed. [4]

ACR3-1314:

The case vehicle, a 1995 Hyundai Accent four-door sedan, was travelling southbound on an urban arterial. A 1992 Honda Civic, travelling ahead of the case vehicle, stopped in traffic. The driver of the Accent braked; however, the front of his vehicle struck the rear of the Civic. Minor damage resulted to the front bumper and hood of the Accent (12FDEW1). The corresponding direct damage to the rear of the Civic was limited to the rear bumper assembly, with induced damage to the spare wheel well (06BDLW1).

Figure 2. 1995 Hyundai Accent

The 35-year-old male driver of the Accent was using the available three-point seat belt correctly, with his seat positioned fully rearward, when the driver's air bag deployed. He sustained only a minor contusion to his left hand.

The right-front passenger was a 4-year-old male. He was 107 cm (3'6") tall, with a mass of 18 kg (40 lb). Before commencing the trip, the driver, the child's father, had buckled the passenger's seat belt with the torso portion of the seat belt behind the child's back. The passenger's seat was adjusted to the mid-position for its range of travel. The driver stated that the child was leaning forward, he thought to play with the radio controls, just prior to the crash.

As a result of the deployment of the right-front air bag, the child received a large abrasion to the right side of the neck and face, and a thermal burn to the right cheek. Complete dislocation of the spine, at C1 and the base of the cranium, was accompanied by complete transection of the spinal cord, and a large haematoma in the region of C1-C7. The right atrium of the heart was bruised, and portions of skin were avulsed from the little finger and wrist of the right hand. In addition, there was head contact with the floor-mounted transmission shift lever resulting in a contusion to the occipital region.

Subsequent to the real-world crash involving the Accent, Transport Canada undertook a series of static air bag deployments using a surrogate child dummy. The tests showed quite clearly that minor changes in the dummy's position had a dramatic effect on the air bag's deployment characteristics. Specifically, physical evidence suggested that, prior to impact, the child was bracing with the right hand and arm against the dashboard. The position of the arm resulted in the deploying air bag being redirected so as to apply load directly to the child's head, creating rotation, and placing the neck into hyperextension. [5]

ASF2-1802:

The case vehicle, a 1994 Plymouth Sundance four-door hatchback, was travelling along a two-lane undivided urban road when it drifted off the right side of the roadway and struck a wooden utility pole. Vehicle damage was minimal and was concentrated on the vehicle's front bumper and grille (12FREN1), with a maximum crush of 18 cm.

The driver was a 58-year-old female. She was fully restrained, and had her seat located fully forward with the seatback upright. The crash occurred directly outside a hospital where she was immediately examined, but was pronounced dead.

The autopsy indicated minor contusions to the right upper arm, left arm and to the left chest. Death resulted from a 0.6 cm tear to the root of the left main pulmonary artery with cardiac tamponade. The pathologist noted that there was no pre-crash degeneration of the arterial tissue.

Figure 3. 1994 Plymouth Sundance

The driver's blood alcohol content was found to be at the legal limit. This fact, in combination with the shallow angle of departure from the roadway, the lack of evasive action, and the injury pattern to the thorax, led to the conclusion that the driver had fallen asleep and was slumped directly on top of the air bag module at the time of collision. [6]

ACR3-1919:

A 1996 Lexus ES300 four-door sedan was travelling southbound on a snow and ice covered residential street. The driver failed to negotiate a left curve and ran off the road to the right. The vehicle travelled across the lawn of a residence, striking a small sapling, breaking through two wooden fences, and finally impacting the corner of a garage. The latter impact resulted in 19 cm of crush to the left-front bumper (12FLEW1) and the deployment of both front air bags.

Figure 4. 1996 Lexus ES300

The driver of the Lexus was a fully-restrained 44-year-old female. The investigating police officer indicated that the driver's seat was positioned close to the steering wheel. Subsequent detailed examination of the air bag assembly identified cosmetic transfers on both the air bag cover and fabric. These witness marks indicated that the driver's head was in extremely close proximity to the air bag module at the time of deployment.

The driver was unresponsive at the collision scene. She was transported to hospital where attempts at resuscitation were unsuccessful. No autopsy was conducted. The cause of death was stated as closed head injury. Other recorded injuries were contusions to the face, chest, and upper right arm, and a burn to the middle and index fingers of the left hand. [7]

ASF2-1505:

A 1992 Ford Tempo four-door sedan was travelling southbound along a two-lane, undivided rural highway. The road was wet as there was light precipitation. A vehicle ahead of the Tempo braked. The Tempo's driver also braked, but lost directional control. The car crossed the centre line and entered the east ditch. The front of the Tempo struck the back slope of the ditch (12FDEW1); however, there was no measurable crush. As a result of the impact, the driver's air bag deployed.

The driver, a 79-year-old female, was fully restrained with her seat in the forward of middle position. Emergency medical personnel arrived within 15 minutes of the collision. The driver was coherent and complaining of chest pain. She was removed from the vehicle and transported to hospital. Later the same day, medical complications arose and the driver was transported to a trauma centre where she died early the next morning.

Figure 5. 1992 Ford Tempo

The driver sustained a comminuted fracture of the left lateral mass of C1, multiple bilateral rib fractures, a lacerated aorta, a fractured sternum, minor contusions, lacerations and abrasions to the face, chest and extremities. [7]

ASF2-1022:

An eastbound 1993 Pontiac Sunbird LE was stopped at a red traffic signal. The case vehicle, a 1995 Geo Metro four-door sedan, also eastbound was approaching the intersection. The Geo Metro's driver braked, but the font of this vehicle struck the rear end of the Sunfire.

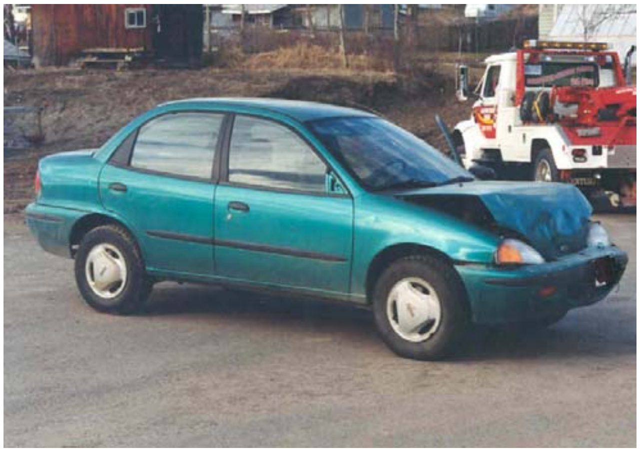

Figure 6. 1995 Geo Metro

The Sunbird sustained damage across the entire rear bumper (06BDLW1). The maximum crush was approximately 15 cm at the right rear corner. The Geo Metro sustained direct damage to the front bumper, headlights, and hood, across the full width of the car, with a maximum crush of 5 cm, measured at the centre of the vehicle (12FDEW1). Both front air bags in the Geo Metro deployed in the crash.

The Geo Metro's driver was a fully-restrained, 21-year-old female who was uninjured in the crash. There were two children in the rear of the vehicle, an 11-year-old male occupying the left-rear seat and a 4-year-old male in the right-rear seat. It is not known if either of these children were restrained; however, neither sustained any injury.

In the right-front passenger seat was a 13-year-old female who was holding a 13-month-old male in her lap. Neither occupant was restrained. It is likely that both of these occupants slid forward out-of-position during pre-impact braking and prior to air bag deployment.

The 13-year-old female sustained a minor laceration to her face, while the 13-month-old male was fatally injured. The injuries to the infant included anterior displacement of C4-C5 with complete transection of the spinal cord; a subdural haematoma; abrasions and contusions to the face.

ASF3-9616:

A 1999 Oldsmobile Alero two-door coupe was travelling northbound on a two-lane, undivided rural arterial. The driver negotiated a sweeping right hand curve and entered a straight section of road. The vehicle travelled over the centre line, crossed the southbound lane, broke through a snow bank on the west shoulder and continued down a steep snow covered embankment.

Near the bottom of the embankment, the left front wheel struck a large rock, breaking the left aluminum control arm. The vehicle continued forward and the front cross-member of the engine cradle struck another protruding rock. The cross-member was displaced rearwards approximately 5 cm (00UFCW1). The event data recorder (EDR) in the vehicle indicated a ΔV of 15 km/h resulting in deployment of the driver's air bag.

Figure 7. 1999 Oldsmobile Alero

The 83-year-old, female driver was 162 cm (5'4") tall with a mass of 68 kg (150 lb). The driver's seat was 7 cm rearward of full forward. The driver's three-point seat belt was equipped with an energy management retractor that was not activated. There was no loading evidence on the restraint; however, restraint usage was confirmed by data recovered from the EDR, and by blood splatter on a portion of webbing that would have been in a retracted position had the belt not been extended.

The driver was found unconscious and bleeding from the nose. She was transported, by ambulance, to hospital where she continued to be unresponsive. A closed head injury was diagnosed. No CT scan was performed. A C-spine film was clear from C3-C7, other than for typical degenerative changes.

The driver expired six hours after arriving at the hospital. Results from a post-mortem examination indicated that the driver had sustained a diffuse subarachnoid haemorrhage, bilateral coning of the cerebellar tonsils, subluxation of the atlanto-occipital joint, and diffuse contusions of the upper cervical spinal cord at C1-C2. In addition there was a periorbital haematoma to the left eye, a contusion to the left eyebrow, and bruising to the extremities.

ASF3-9617:

The case vehicle, a 2000 Acura Integra two-door coupe, was southbound and was stopped in a line of traffic at a red traffic signal. The front end of a 1996 Chevrolet Cavalier approaching from the rear of the Acura struck the Acura's rear bumper. The front end of the Acura was pushed into the rear of a 1998 Dodge Caravan which, in turn, was pushed into the rear of a 1995 Mazda 626 Cronos.

Figure 8. 2000 Acura Integra

The double hit to the Acura resulted in minor damage to both the rear and front ends of the vehicle, with no measurable crush to the exterior of either bumper. Deformation of the structures under the bumper fascias measured approximately 1 cm (12FDLW1). An on-board event data recorder indicated a ΔV for the frontal impact of 19 km/h, resulting in deployment of the driver's air bag.

The steering column showed evidence of loading in the form of partial shear capsule separation. There was an abrasion from the air bag on the windshield wiper stalk. There was trace evidence of occupant head contact on the windshield, and a knee contact on the lower portion of the steering column shroud. The driver's seatback was twisted clockwise.

The 47-year-old, female driver of the Acura was 147 cm (4'10") tall with a mass of 56 kg (124 lb). The driver's seat was in the full forward position, and the seatback was fully upright. The tilt-steering wheel was in the lowest adjusted position. No loading evidence was observed on the seat belt tongue or D-ring. There was evidence that the driver was unrestrained, and in close proximity to the air bag module at deployment. Clothing transfers were identified on the two halves of the air bag cover, with corresponding transfers on the occupant's blouse in an area over the centre of her chest. In addition, damage to the leather jacket worn by the driver was indicative of occupant interaction with the air bag.

The driver was found in the vehicle, unconscious, and bleeding from the nose. When emergency rescue personnel arrived at the scene, the driver had no vital signs. Results from an autopsy indicated that the driver has sustained complete transection of the aorta at the level of the 5th intercostal arteries; bilateral rib fractures; a fractured sternum; bilateral haemothoraces; small lacerations along the lower border of the spleen; mesenteric bruising to the left upper quadrant of the intestine; mediastinal haemorrhage; a laceration of the oral mucosa, to the left of the upper median frenulum; periesophageal haemorrhage; an abrasion to the anterior neck; abrasions and contusions to the left elbow. No skull fracture was observed, the brain anatomy was normal, and the vertebral column, including the cervical spine, was intact.

ASF3-9628:

The case vehicle, a 1994 Plymouth Voyager minivan, was stopped at a traffic-light controlled intersection. Ahead were a 1996 GMC Sierra 4x4 pickup truck and a 1997 Toyota Avalon. The light turned green and the vehicles proceeded across the intersecting road. Empty refuse containers were blown onto the road by the wind. A vehicle in front of the Toyota stopped. The Toyota, and the GMC, which was immediately behind the Toyota, also stopped. The driver of the Plymouth braked; however, the front of the minivan (12FDEW2) struck the GMC's rear bumper (06BZLW1).

Figure 9. 1994 Plymouth Voyager

The underride impact configuration resulted mainly in damage above the Plymouth's bumper. The hood was buckled, and the upper radiator support was deformed rearward against the engine. A maximum crush of 38 cm was recorded at the level of the edge of the hood. There was direct contact to the rear bumper of the GMC pickup truck, with a maximum crush of 3 cm.

Based primarily on the damage to the collision-involved vehicles, a pre-impact speed of 30 km/h was estimated for the Plymouth, with a corresponding ΔV of 18 km/h. Both front air bags in the Plymouth deployed in the crash.

The driver of the Plymouth was a fully-restrained, 40-year-old male. His seat was in the rearward of middle position. The steering column showed evidence of loading in the form of partial shear capsule separation. No evidence of occupant contact on the air bag was identified. There was an abrasion, from knee contact, on the right side of the lower steering column. The driver was uninjured.

The right front passenger was an 8-year-old male. He was 132 cm (4'4") in height, with a mass of 34 kg (75 lb). The passenger's seat was in the full rearward position. The seatback was twisted clockwise as a result of occupant loading to the outboard side.

Inspection of the child's lap/torso restraint system revealed very faint striations in the main slot of the modified locking tongue, and on the locking bar. In addition, bloodstains were located on a portion of the webbing that would have been in the retracted position, had the seat belt not been extended. The adjustable D-ring was in the highest position.

The driver, who was the child's father, indicated that the right front passenger was restrained by the lap/torso seat belt. However, he further indicated that his son would sometimes position the torso portion of the belt over the side of his shoulder. The collision circumstances indicate that the child was using only the lap portion of the seat belt at the time of air bag deployment.

There was no evidence of contact by the passenger with the windshield, windshield header, right A-pillar, air bag module door, or the dashboard. There were clothing transfers present on the passenger's air bag, primarily on the top surface and front face of the air bag fabric.

As a result of the crash, the child sustained near complete transection of the lower brain stem/upper cervical cord with multiple intra-cerebral white matter haemorrhages; transection of the trachea; multiple cortical contusions; diffuse subarachnoid haemorrhage; lacerated tectorial membrane with avulsion fracture of the left occipital condyle; diffuse contusion involving the left side of the lower face and neck with soft tissue edema; multiple confluent superficial abrasions to face and neck; avulsion of both mandibular and maxillary central incisors; extensive haemorrhage involving the anterior and posterior strap muscles of the neck; and loss of normal kyphosis of the neck with irregular movement of the head on palpation.

ASF3-1904:

A 1997 Dodge Grand Caravan minivan was eastbound on a four-lane, undivided, urban arterial. The Caravan had just travelled through an intersection when a 1994 Ford Explorer, also eastbound, and in front of the minivan, came to a stop because downstream traffic had stopped. The driver of the Caravan braked hard but was not able to avoid colliding with the rear end of the Explorer (06BDLW1). The impact propelled the Explorer forward, causing it to rear-end a vehicle ahead of it. The Caravan underrode (12FDEW2) the Explorer and was wedged underneath the latter at rest.

Figure 10. 1997 Dodge Grand Caravan

The Caravan sustained direct contact damage to the front bumper and grille area. At bumper level, the damage was mainly to the fascia. The steel bumper reinforcement beam behind the fascia sustained minimal damage. Above-bumper components such as the hood, grille, the radiator, the radiator support, the leading end of the front left fender, and the left headlight assembly all sustained damage. A maximum crush of 20 cm was measured at the level of the radiator support. Contact to the Explorer was to the rear bumper with a maximum crush of 10 cm.

The driver of the Caravan was a 56 year-old male whom a witness described as about 173 cm (5’8”) tall with a mass of 113 kg (200-300 lb). The driver’s seat was in the full rear position. The police report indicated that the driver was belted, but no witness marks were identified on the restraint system. The driver’s air bag deployed. The upper and the lower portions of the steering wheel were deformed forward. The police reported that the driver was uninjured.

The right front passenger in the Caravan was a 6-year-old female with a height of 142 cm (4’8”) and a mass of 38 kg (84 lb). A bystander, who was first to assist at the scene immediately after the collision, reported that only the lap portion of the three-point seat belt restrained this child, and that the torso portion was located behind the child’s back.

The seat belt had been placed around the child by her mother at the start of the trip. Both the child’s mother, and the driver of the case vehicle, reported that the seat belt was initially positioned correctly. The mother indicated that, on previous occasions, the child had been known to slip the torso belt either over her head or under her arm. The driver was not aware of the child repositioning the belt system at any point during the trip. The driver’s recollection was that, following the crash, the child was tangled up in the shoulder belt, and that he slipped the shoulder belt behind her back.

Examination of the seat belt system identified a number of witness marks on the seat belt tongue and D-ring. Blood stains on the webbing were located in an area which, with the lap belt extended across the child's waist, would have been close to the seat belt buckle assembly. Abrasions located on the plastic coating of the seat belt tongue were consistent with occupant loading of the system in the collision. No corresponding transfers on the lap belt webbing could be identified, and thus the adjusted length of the lap belt could not be determined.

Abrasions were also identified on the plastic coating of the D-ring. An unusual feature of these abrasions was their orientation at a small angle towards the rear of the vehicle. Normal occupant loading patterns (i.e. the occupant moving forwards in a frontal crash) would make such abrasions run down and at an angle towards the front of the vehicle. No corresponding transfer marks were identified on the torso belt webbing so that the adjusted length of torso belt could not be determined.

The pattern of witness marks on the passenger's seat belt indicates that the lap belt was in place, but the shoulder belt was behind the child's back at the time of air bag deployment. It is believed that the rear-oriented abrasions on the D-ring were the result of the air bag forcing the child rearwards against the locked torso belt webbing.

As a result of the collision, the child sustained a severe head injury with a subarachnoid haemorrhage and swelling of the brain; bruising bilaterally to the inner lower eyelids; extensive bruising to the lower lip with avulsion of the inner aspect; an extensive abrasion over the anterior cheek, nose, and chin; and bruising on the underside of the chin.

Collision Analysis and Crash Testing

All of the fatal collisions in this series have been subject to detailed research involving consideration of the sequence of collision events, crash severity, occupant kinematics, and the likely mechanisms of occupant injury.

The results of follow-up test programmes, for incidents which have not been previously reported in the literature, are described below.

ASF3-9616: 1999 Oldsmobile Alero

For this case, testing, using static air bag deployments in an exemplar 2000 Oldsmobile Alero and a Hybrid III 5th percentile female dummy, was not definitive in identifying a specific injury mechanism.

Limitations in the dummy, specifically, the lack of flexibility in the upper thorax, head and neck regions, restricted the extent to which realistic positioning, representative of the actual situation in the subject collision, could be achieved. Furthermore, the advanced age of the subject driver was an additional confounding factor both in matching dummy characteristics and in the assumed injury tolerance levels.

Nevertheless, in general, the test results were supportive of the supposition that the observed fatal head and neck injuries were consistent with direct loading by the deploying air bag in the real-world crash.

ASF3-9617: 2000 Acura Integra

The fact that little damage resulted to any of the vehicles involved in this multiple collision is indicative of the relatively low severity of the event. The event data recorder installed in the Acura indicated that the vehicle had experienced a ΔV of 19 km/h when the air bag deployment command was issued. This figure is consistent with ΔV estimates based on crush energy analysis, given the range of uncertainty which exists in the data used in the computations.

Staged collisions, designed to evaluate the dynamic effects of dummy loading, were undertaken using an exemplar Acura and a moveable deformable barrier (MDB). The MDB was ballasted to the mass of the impacted Caravan, and had an aluminum honeycomb face. The impact speed of the Acura in the rear-end crash with the stationary MDB was 16 km/h. In the tests, the front-end damage which resulted to the Acura was similar to that observed in the real-world incident. While these tests do not reconstruct the actual crash, the combination of the test speed and resulting vehicle damage supports the above-noted indication of the low severity of the case collision.

The Acura's driver was of small stature. She had the seat adjusted fully forward, with the seatback upright. The tilt-steering wheel was in the fully down position. There was no clear indication from individuals present at the collision scene as to whether or not the driver in this case was belted. Given the low severity of the crash, the driver's low mass, and the fact that the air bag evidently distributed some of the collision forces, the lack of any loading evidence on the driver's seat belt system was inconclusive with respect to belt use.

Witness marks on the occupant's clothing resulted from interaction with components of the air bag system. In particular, marks on the driver's blouse, attributed to contact with the air bag module cover flaps, were not consistent with seat belt webbing following a path across the driver's chest, and thus indicated that the driver was unrestrained. This would be consistent with the driver being out of position at deployment, having her chest close to the steering wheel system, and making head contact with the windshield.

The witness marks on the driver's clothing showed that she was in extremely close proximity to the module at the time of deployment. Static testing was undertaken using a 5^{th} percentile female dummy as a surrogate occupant. From high-speed video images of these tests, witness marks on the dummy's clothing were confirmed as being due to contact with the air bag module cover flaps.

These marks were similar to those identified in the case incident, thus corroborating the driver's close proximity to the air bag module. With the dummy in such close proximity, the pattern of air bag deployment also gave rise to contact of the air bag fabric with the windshield wiper stalk located behind the steering wheel, the situation which was observed in the case vehicle.

The pattern and severity of the thoracic trauma sustained by the Acura's driver were consistent with the results of the tests when the dummy was in close proximity to the air bag module at the time of deployment. In particular, the rib deflections measured on the dummy were of the order of 50 mm, a level which could well result in major chest injury.

Figure 11. Chest-on-module out of position test

The case collision was of low severity and the fatal thoracic injuries sustained by the driver of the Acura resulted from forces applied to the chest by the deploying air bag.

The test results suggest that increasing the distance between the dummy chest and the air bag module by as little as 50 mm reduced the peak thoracic deflections of the dummy by approximately half. A properly worn seat belt may have provided sufficient restraint to prevent the driver from entering into such close proximity to the air bag module.

The comprehensive testing undertaken with respect to the investigation of the case incident highlighted significant limitations with existing out-of-position procedures. In particular, the test protocol designed to maximize loading to the chest, as defined by NHTSA in their final rule for FMVSS 208, was found not to produce the worst case scenario.

The pertinent dummy positioning procedure has been modified by Transport Canada to ensure a more stringent "chest-on-module" loading environment. [8] This enhanced testing procedure will be included in a proposed revision to Canadian Motor Vehicle Safety Standard 208 (Occupant Restraint Systems in Frontal Impact). [9]

ASF3-9628: 1994 Plymouth Voyager

The damage to the involved vehicles was indicative of the low severity of this collision. Calculations based on measurements of the vehicle crush, and of the post-impact trajectories of the vehicles, suggested that the pre-impact speed of the Plymouth was of the order of 30 km/h, with a resulting ΔV of 18 km/h.

The case vehicle was old and there were a number of wear marks indicating regular usage on the seat belt systems. Loading evidence on the belts, resulting from the subject collision, was slight; however, this was not unexpected given the masses of the occupants involved, the low crash severity, and the fact that the air bags off-loaded the seat belt restraining forces for the front seat occupants.

For the fatally-injured child, it is clear that the lap portion of the seat belt system was in use, based on faint striations on the tongue, and the fact that blood had been transferred onto the webbing in a location where the lap belt must have been extended from the stowage position. Blood found on the seatback was contiguous with traces of blood detected on the torso portion of the seat belt suggesting that the torso belt was behind the child's back.

The pattern and severity of injuries sustained by this child, being exclusively to the head and neck, are indicative of the child's head being in close proximity to the air bag at the time of deployment. Thus, it is believed that the child was restrained only by means of the lap portion of the three-point seat belt.

Static Air Bag Deployment Testing

A test programme to investigate the injury mechanisms and kinematics associated with the fatally injured child incorporated a series of 5 static air bag deployments, carried out with a Hybrid III 6-year-old child dummy, and a Q6 6-year-old child dummy in an exemplar 1994 Dodge Caravan.

The test programme was initiated by an examination of occupant fit in the right front passenger seat of an exemplar vehicle. A male child matching the anthropometry of the child involved in the case incident was placed in the front passenger seat and asked to assume various seating positions with and without the seat belt.

Particular attention was focused on the length of the extended belt with and without slack. Belt routing, specifically the routing of the torso belt, was examined with the torso belt placed correctly, that is across the child's chest as designed, and incorrectly, behind the child's back. The extent to which a belted child could be expected to move forward in a dynamic crash situation was examined, albeit statically, to estimate the most probable position of the head and neck at the time of air bag deployment, and to establish possible contact points.

Two types of child dummies each representative of the anthropometry of an average six-year-old child were used to measure responses during static air bag deployments. Each dummy was positioned in the front passenger seat in such a way as to attempt to simultaneously: represent the seating positions observed with the child in the case collision; replicate elevated responses in the body regions where the fatal injuries were documented; and reproduce witness marks and other damage within the vehicle compartment.

While both dummies lack the suppleness and joint motion characteristics of a human child to permit the exact replication of position immediately prior to air bag deployment, it was possible to eventually satisfy all three requirements and substantiate the likely position of the child with a good degree of certainty.

The conclusive test set up consisted of the Hybrid III 6-year-old dummy seated in the centre of the front passenger seat, flexed at the hips to the extent possible, and with the arms extended. The hands of the dummy were secured to the dashboard on either side of the air bag door opening to simulate inertial loading. The dummy's chin was raised, though to a smaller degree than would be expected in the case of a child. The dummy's neck is significantly stiffer than that of a child and will not extend, or allow the chin to point upwards easily. Forcing the dummy's chin up applies a pre-load to the neck, which can confound neck response values. Thus, the position achieved is perhaps not ideal but, nevertheless, is still considered representative. The use of the Q6 6-year-old dummy was abandoned due to its inability to be installed in a position representative of the male child in the subject collision.

Figure 12. Air bag interaction with head of child dummy

Damage to the interior of the vehicle was replicated only in the final, conclusive test with the arms braced. In the absence of such bracing of the arms, the bag tends to deploy immediately downwards, tearing the lower corners of the vinyl surrounding the air bag opening. The air bag must be deflected upwards to prevent this tearing from occurring. The windshield did not break or shatter in any of the static deployments. It is believed that the windshield cracking occurs only in a dynamic situation where there is inertial loading and deformation of the physical structures occurring simultaneously.

Based on the above testing, the child kinematics can be summarized as follows: During pre-crash braking, the pelvis of the child slides forward until all slack is removed from the lap portion of the seat belt; the child's upper torso then pivots forward over the belt. Seeing the impending collision, the child raises his arms in self-protection such that at the moment of impact his body weight is driven into the dashboard through his arms. The air bag deploys and unfolds along the arms, until it contacts the chin and loads the head and neck. The air bag remains in a horizontal plane and does not tear the vinyl material surrounding the air bag unit in the dash.

The tests identified high levels of air bag loading to the dummy's head and neck, with a notable absence of loading to the chest. The child's chin would have been at arm's length from the deploying air bag. The responses measured surpassed established injury criteria for the head and neck and are believed to be consistent with the documented injuries.

Vehicle-Vehicle Crash Testing

A dynamic reconstruction of the case collision was carried out to quantify the severity of the underride crash configuration. A child dummy was used to try to replicate the hypothesized occupant kinematics for the right front passenger. In addition, a second dummy, located in the rear seat, was used to confirm the likely outcome for a properly restrained child placed in the rear seat.

In this test, an exemplar 1994 Dodge Caravan, travelling at 33.7 km/h, impacted the rear of a 1996 GMC Sierra 1500 pickup truck. The vertical geometry of the two test vehicles was set up so as to reproduce the underride configuration that was known to have occurred in the real-world incident.

The damage resulting to the 1994 Caravan from the staged collision was very similar to that of the 1994 Plymouth Voyager in the real-world crash. Thus, the pre-impact speed of the bullet vehicle in the actual collision was determined with some certainty, and the low severity of the subject incident confirmed.

Unfortunately, in the dynamic situation, the pre-impact position of the head of the dummy in the right front passenger's seat was not optimal. This caused the bag to slip over the head, compressing the child downwards into the seat. No damage to the windshield resulted from the air bag deployment in this situation.

The child dummy in the rear seat rode down the crash without incident. Here, the dummy responses were all well below the injury tolerance values. Hence, a child in the rear seat, restrained by a lap/torso belt in combination with a booster seat, would very likely not have suffered any injury in the case collision.

<u>Conclusions from Static and Dynamic Testing</u>

The test scenario of a lap-belted child occupant, with the shoulder belt located behind the child's back, and the child leaning forward bracing against the dashboard, is believed to be appropriate in the case collision.

The fact that the outstretched arms on the dummy caused the air bag to load the head and neck without significant chest contact is consistent with the injury patterns observed in the real-world crash. The absence of dashboard tearing in the region of the air bag, which was only achieved when the arms were braced, is consistent with the documented findings of the case vehicle. Consequently, it is believed that this was the situation for the child involved in this collision, and that the injuries sustained were the result of direct air bag load.

Furthermore, the response of the dummy in the rear seat, observed during the dynamic reconstruction with the 1994 Caravan, strongly supports the premise that had this child been located in the rear seat, in an appropriate child restraint system, he would not have been subjected to fatal head and neck injuries. In fact, the likelihood is that he would have been uninjured.

ASF3-1904: 1997 Dodge Grand Caravan

With the exception of the model year of the case vehicle, and hence the specific type of passenger air bag module with which the vehicle was equipped, the circumstances of this collision are remarkably similar to those of the previous case (ASF3-9628).

In the subject crash (ASF3-1904), the physical evidence identified on the right-front passenger's restraint system suggests that the young child occupying this seat was using the lap portion of the seat belt across her pelvis, with the torso belt positioned behind her back. Had the shoulder belt been across the child's chest, the abrasions on the D-ring that resulted from collision loading would have been oriented down and towards the front of the vehicle. The fact that the abrasions were towards the rear of the vehicle most likely resulted from the torso belt being located behind the child's back and the child being displaced rearward against the shoulder belt due to air bag deployment.

In the crash, the positioning of the passenger's seat belt system prevented the shoulder belt from restraining the forward movement of the child's torso. As a result of pre-impact braking, and the subsequent collision, the child's head and upper body would have been pitched forward into the deployment zone of the air bag. Interaction between the deploying air bag and the child then resulted in the fatal injuries sustained.

The passenger air bag for the Caravan/Voyager was redesigned in 1996 as a mid-mounted system, with the module door essentially in the face of the dashboard, as opposed to the top-mounted system used previously, where the module door was located on the upper surface of the dashboard and opened upwards.

In order to investigate the specific situation for the subject collision, a static test was conducted on an exemplar 1997 Dodge Grand Caravan. A 6-year-old Hybrid III dummy was positioned in the right front passenger seat. Both arms of the dummy were extended forwards with the palms of the hands pressed against the dashboard on either side of the air bag module.

As the air bag deployed, the fabric unfolded along the arms, contacting the dummy's head with minimal chest loading. The bag applied tensile forces to the neck, and produced hyperextension of the head/neck complex. The test results indicated elevated head and neck responses. In contrast, loading to the chest resulted in only minor deflections and would not be expected to have contributed to any chest injury. These dummy responses are consistent with the documented injuries in the case collision.

Following the static deployment, the condition of the vinyl fascia surrounding the air bag module was comparable to that reported for the case vehicle. The damage to the right side of the windshield that was observed in the real world crash was not reproduced in the static test set-up. Such breakage is believed to be associated with inertial loading of the air bag into the windshield, a phenomenon which cannot be reproduced statically.

Discussion

The Canadian field experience with air bag systems has been similar to that of the United States; however, a significantly lower level of fatalities directly attributed to air bags has been seen in Canada. It is believed that this is a result of higher levels of usage for both seat belts and child restraint systems in Canada compared to the U.S.

The good news for our American traffic safety colleagues is that the number of air bag induced fatalities in the U.S. has fallen dramatically in recent years, and particularly following the introduction of depowered air bags in 1998. No doubt this reduced level of fatalities has been due in part to the availability of improved air bag designs, but also reflects heightened public awareness to the risks involved and to the available countermeasures.

In Canada, air bag induced fatalities have been found to be associated with occupants in close proximity to air bag modules at the moment of deployment. Additional factors of note have been the non-use of seat belts in some instances and, in others, the misuse of seat belts, notably children using only the lap portions of three-point seat belts.

Adult Fatalities

In three cases (ACR3-1919, ASF2-1505 and ASF3-1916), where fatally-injured drivers were fully restrained prior to impact, the collisions involved relatively complex vehicle dynamics. In particular, the crashes frequently involved multiple impacts prior to air bag deployment, thus affording opportunities for the belted occupants to be jostled out of position. Another scenario, believed to have been the case in one of the reported incidents (ASF2-1802), was the belted driver being slumped over the steering wheel at the point of impact when the air bag was deployed.

The other two cases involved unrestrained drivers. One individual was involved in a multiple-impact crash that resulted in her chest being adjacent to the air bag module at deployment (ASF3-9617), while the other was believed to have been slumped over the steering wheel when the collision occurred (ACRS-1103).

Clearly, the issue of proximity to the air bag module at the time of deployment is paramount in terms of the potential for adverse occupant-bag interactions. In this respect, it is noteworthy that all four of the fully-restrained, fatally-injured drivers were female, of short stature, and had their seats adjusted to forward-of-middle positions, initially positioning them relatively close to the steering wheel and hence to the air bag module.

Thus, adopting a driving position as far away from the air bag module as possible, while maintaining the ability to safely reach the vehicle controls, is an eminently prudent approach to minimize the risk of air bag induced injury. Such a step must be combined with the proper use of the available three-point seat belt. The lap and shoulder belts should be properly positioned over the pelvis and across the rib cage to ensure an appropriate load path and to adequately distribute the collision forces. Both belts must also be properly adjusted to remove any slack and thus minimize occupant excursion. [10]

Child Fatalities

The concern over adverse interactions between air bags and child passengers has been the subject of much discussion and has resulted in many safety agencies issuing warnings about keeping children out of seating positions in which air bag systems are installed.

No less important is the fact that all children riding in automobiles must be protected by a child restraint system or seat belt assembly appropriate to their physical characteristics. Transport Canada has published guidelines to inform parents and guardians how best to restrain children in their care in order to provide optimal protection in the event of a crash. [11]

Nevertheless, as noted above, a number of Canadian child fatalities associated with air bag deployments have been investigated by the authors. The cases involving children that have been summarized above share a common tragic element. Each of these fatalities could have been prevented had the child been seated in the rear seat or failing this, had the restraint system been used correctly.

Canadian Countermeasures

As a result of Canadian field experience with air bag deployments, and concerns over similar data published by the National Highway Traffic Safety Administration (NHTSA) in the United States, Transport Canada issued a Road Safety Leaflet: “Safety Issues for Canadians: Air Bags” in June, 1996. [12]

Subsequently, a series of Ministerial press releases, safety brochures, videotapes, and web pages have been developed and issued by Transport Canada on the subject of child safety with respect to air bags. Similar messages have been disseminated by many safety organizations and motor vehicle manufacturers.

In November 1996, the Minister of Transport announced that automobile manufacturers had agreed to equip future Canadian motor vehicles with less aggressive air bags. [13] Initial experience with these “second-generation” air bags suggested that a reduction in air bag induced injuries resulted, without any degradation of the level of supplementary protection afforded to motor vehicle occupants. [14]

The changes to air bag systems installed in new vehicles obviously has no effect on the deployment characteristics of air bags present in the existing vehicle fleet. In November 1998, as a result of concerns over the vulnerability of certain segments of the population to adverse interactions with first-generation air bag systems, the federal, provincial and territorial governments agreed on a national programme of air bag deactivation. This programme provided individuals with information relating to air bags, the specific risks which might be of concern, and a mechanism to deactivate one or more air bags in a vehicle where this was deemed appropriate [15].

Future Action

The tragic consequences of a number of real-world collisions, and the graphic results of Transport Canada's test programme, highlight the importance of keeping occupants out of the direct path of the deploying air bag, especially early in the deployment phase where the risk of serious injury is greatest.

In fact, the primary risk to vehicle occupants is being in close proximity to the air bag module, and hence to significant loading by the air bag should it deploy. This highlights the need for adult occupants to be aware of the need to position their seats as far rearward as practicable, and to ensure that seat belts are used correctly. It is also for this reason that safety advocates promote the need to locate vulnerable occupants, such as children, away from air bag equipped seating positions, and require the proper use of appropriate restraint systems. Clearly, these messages are still not reaching the entire intended audience, and the safety community must redouble its efforts in this regard.

Automobile manufacturers continue to improve occupant restraint technologies. Many new vehicles are equipped with seat belt pre-tensioners and load-limiting systems, that restrain occupants early in the crash phase, and mitigate the potential for serious chest injury. Similarly, advanced sensing systems (e.g. weight sensors, ultrasonic proximity detectors) detect children and out-of-position occupants and work in concert with "smart" air bags to either suppress deployment, or to tailor the deployment to specific collision and occupant characteristics. Advanced air bags often feature dual-threshold systems, that provide air bag deployments at low crash severities for unbelted occupants, but require higher crash severity for deployment in the case of belted occupants. Similarly, dual-stage air bag inflators provide either low or high output deployment based on both occupant restraint status, seat position and crash severity. Further refinements to air bag designs (e.g. recessed modules, fold patterns, tether systems) have resulted in air bag deployments being less aggressive to occupants. All of these advanced occupant restraint systems are being brought to market and, consequently, the risks of air bag induced injuries are lessened.

Nevertheless, even if all of these advanced safety measures are completely successful, the potential for adverse air bag-occupant interactions will remain for individuals utilizing older models in the existing vehicle fleet. Such risks will be present until these vehicles are eliminated from the fleet due to the normal process of attrition. Consequently, dissemination of knowledge as to the risks and appropriate countermeasures must be continued. It seems clear that such programmes must be undertaken in an enhanced manner, if the information is to be provided to more road users, and targeted at those who are most vulnerable.

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The conclusions reached, and opinions expressed, in this paper are solely the responsibility of the authors. Unless otherwise stated, they do not necessarily represent the official policy of Transport Canada.

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