IN-DEPTH INVESTIGATION AND RECONSTRUCTION OF AN AIR BAG INDUCED CHILD FATALITY

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ABSTRACT

A minor rear-end collision resulted in the death of a four-year old child, occupying the right-front seat of the striking vehicle. The child was restrained by means of a lap belt, the shoulder portion of the belt system having been placed behind the child's back. The child was leaning forward, when the vehicle's brakes were suddenly applied, just prior to the crash. The passenger air bag deployed and the child sustained fatal neck injuries.

The case incident was subject to an in-depth collision investigation. Physical evidence associated with the crash, combined with witness statements, and medical data, enabled the vehicle dynamics, occupant kinematics, and occupant contact points to be accurately determined. The collision was subsequently reconstructed using an instrumented child dummy and static deployment of exemplar air bags. A car to rigid barrier dynamic test was also conducted.

High-speed film and video recordings of the tests revealed that even minor changes in the position of the dummy had considerable effect on the post-deployment kinematics. Combining the experience gained from a number of such trials, the real-world event was successfully reconstructed in the laboratory.

INTRODUCTION

Following multiple reports of similar tragic incidents in the United States, this first Canadian case of a child fatality resulting from air bag deployment garnered considerable public attention. The results of an in-depth collision investigation of the incident, coupled with the findings from other Canadian field accident data on air bag deployment crashes (Dalmotas, 1996), led to recommendations from Transport Canada for specific measures to protect children being transported in motor vehicles from air bag-induced injuries.

For the subject case, detailed observations made by the collision investigation team relating to the vehicle dynamics, crash severity, and the resulting occupant kinematics correlated well with the injuries determined at autopsy, and the recollections of the driver with regard to the pre-crash situation. It was evident that the child was lap-belt restrained, and was leaning forward and to his left, at the time of impact. The resulting fatal injuries were attributed to adverse interaction between the deploying air bag and the out-of-position child.

The level of detail available in this crash presented an opportunity for a reconstruction of the collision in the laboratory, using a child anthropomorphic test dummy (ATD) in a simulated vehicle interior. The ATD was fully instrumented and the series of static air bag deployments were recorded on high-speed film and videotape. Following the series of static tests, a full-scale crash test of a car into a rigid barrier was also conducted.

This paper gives the background to the real-world collision, provides the detailed findings of the collision investigation, in the context of the medical data, describes the test series of static and dynamic air bag deployments, and gives the highlights of the analysis of the resulting data.

COLLISION INVESTIGATION

Pre-Collision Events

On a morning in May, 1996, the father of a family of four awoke early at 5:00 am. Since he had a day off work, and wanted to use the family car, a 1995 Hyundai Accent four-door sedan, he placed both his children safely in the back seat, and drove his spouse to her place of work at approximately 6:30 am. On his way home, he purchased two trees to plant in his backyard, bought some candy for his children, and stopped at a video store. He dropped off his 6-year-old son at school, and then went back home to unload the trees, and have breakfast with his 4-year-old son.

At 10:30 am, he was back in the car with his youngest son, intending to pick up the elder child from school. As a special treat, and at the child's request, he let his son sit next to him in the right front passenger seat.

A few months earlier, this child had outgrown his forward facing child restraint. Ever since, when the right front passenger seat was available, the two children would fight over this seating position but the parents would generally end up putting them both in the rear seat. On this occasion, the father made a rare exception, as he sometimes did when alone with his 6-year-old.

He didn't think twice about any safety issues. He had purchased this family car new, just two months earlier, and it came with all the safety features which he had heard about on television: ABS brakes, three-point seat belts with adjustable D-rings, as well as both driver and passenger air bags. There was no reason for him to believe that his son would be exposed to any danger sitting in the right front passenger seat. Although, he had seen the warning label on the sun visor, he didn't pay much attention to it. He had never actually read it, nor had he studied the owner's manual.

Collision Events

The Accent was travelling southbound in the left lane of a four-lane, undivided, urban arterial, in an area with a posted speed limit of 50 km/h.

A 1992 Honda Civic four-door sedan was travelling in front of the Accent. The Civic stopped as a vehicle ahead was trying to turn left but was prevented from doing so by heavy northbound traffic.

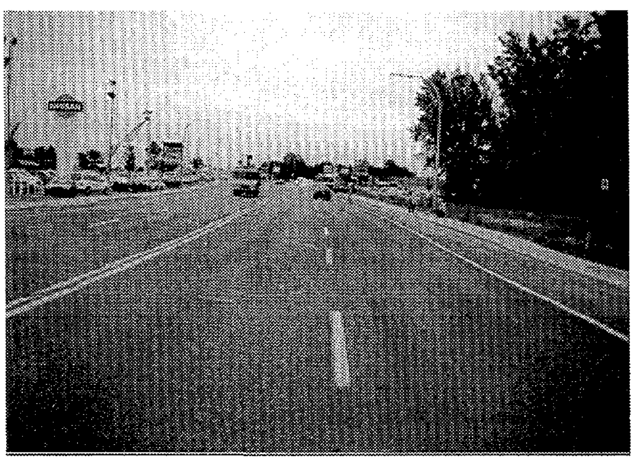

Figure 1. Collision scene looking southbound.

At this instant, the driver of the Accent was inattentive because his child was leaning forward, either to play with the radio controls, or to reach for some candy placed in a foam cup in the cup holder. The driver's eyes left the road for a few seconds as he reached with his right hand to reposition his child in the seat. Re-focusing his attention to the road, he noticed the cars ahead were stopped. He braked hard; however, the front of the Accent struck the rear of the Civic.

Post-Collision Events

The driver of the Accent was aware that the vehicle's air bags had deployed, and that there was something wrong with his son, as the latter was lying on his side, unconscious. He pulled the child out of the car through the driver's door, and quickly carried him over to a nearby medical clinic. Resuscitation attempts were commenced immediately. The child was transported to a local hospital, and was subsequently transferred to a paediatric trauma centre. Cervical spine X-rays revealed an atlanto-occipital dislocation which suggested spinal cord transection at C1. Further aggressive treatment was withheld and the child was officially pronounced dead several hours after the crash (Giguère, 1997).

Vehicle Damage

Minor damage resulted to the front bumper and hood of the Accent (CDC: 12FDEW1). Maximum residual crush, measured at the level of the front bumper, was 5 cm. The radiator support was lightly twisted on both ends and the radiator was leaking. Both headlights were partially detached but were unbroken.

The corresponding direct damage to the rear of the Civic was limited to the rear bumper assembly, with induced damage to the trunk lid and the spare wheel well (CDC: 06BDLW1).

Figure 2. Left-front three-quarter view of the Accent.

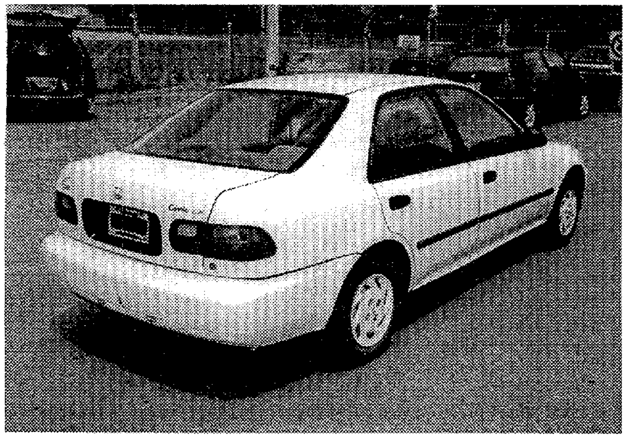

Figure 3. Right-rear three quarter view of the Civic.

Imprints of the Accent's front license plate, hood ornament, and headlights were observed on the Civic's bumper. These were used to position both vehicles and hence to determine the exact collision configuration. This confirmed that the Accent was under braking at impact.

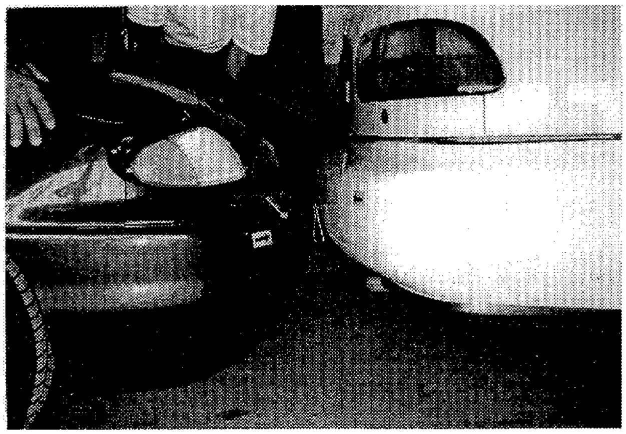

Figure 4. Reconstruction of the impact configuration.

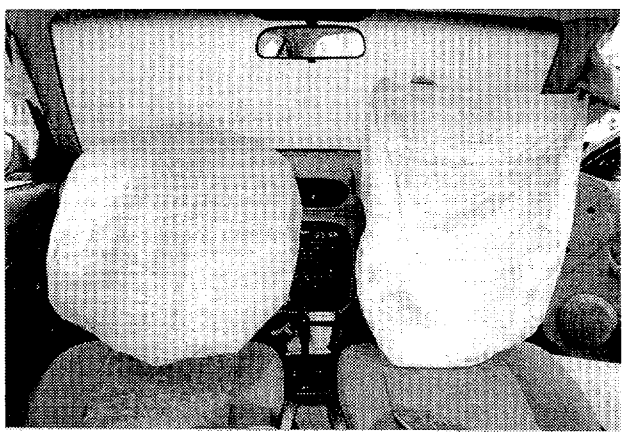

Figure 5. Dual air bags in the Accent.

The Accent was equipped with three-point seat belts with adjustable D-rings, and dual front air bags. Both air bags deployed as a result of the crash.

Occupant Injuries

Driver - The 35 year old, male driver of the Accent was 178 cm (5'10") tall and weighed 113 kg (250 lb). He was seated in a bucket seat that was adjusted fully rearward. He was using the seat belt correctly, as confirmed by observed loading evidence on the system. There were striations on both the D-ring and the sliding tongue, along with a diagonal abrasion on the webbing, corresponding to the location of the D-ring, which was adjusted fully upward.

The driver suffered only a minor contusion to the outside surface of his left hand, probably resulting from his hand being thrown against the side interior surface by the deploying air bag.

Right-Front Passenger - The 4-year-old, male, right-front passenger, was 107 cm (3'6") tall, with a mass of 18 kg (40 lb). The right-front seat was adjusted to the mid-position of its range of travel. The driver believes that he had buckled the child's seat belt prior to departure for the trip; however he does not recall unfastening the belt when he removed the child from the vehicle immediately following the crash. It was the driver's habit to place the shoulder belt behind his son's back because of the child's small stature. Faint loading marks on the seat belt tongue were identified. Consequently, it is believed that the seat belt was indeed in use, and that the child was only using the lap portion of the system at the time of impact.

As the air bag deployed it made forceful contact with the child. Transfer marks from the occupant's green, nylon jacket were found on the fabric on the left side of the air bag, adjacent to the exhaust vent.

Due to contact with the air bag, the child received a large abrasion to the right side of the neck and face. A thermal burn to the right cheek was consistent with the vent location. There was complete dislocation of the cervical spine, between C1 and the base of the cranium, accompanied by a complete transection of the spinal cord, and a large haematoma in the region of C1-C7.

The child's upper torso was propelled rearwards and down by the air bag. His head impacted and broke the floor-mounted automatic transmission shift lever resulting in a contusion (7 cm x 4 cm) to the occipital region. Other injuries noted were contusions to the right atrium of the heart, and avulsion of portions of skin from the little finger and wrist of the right hand.

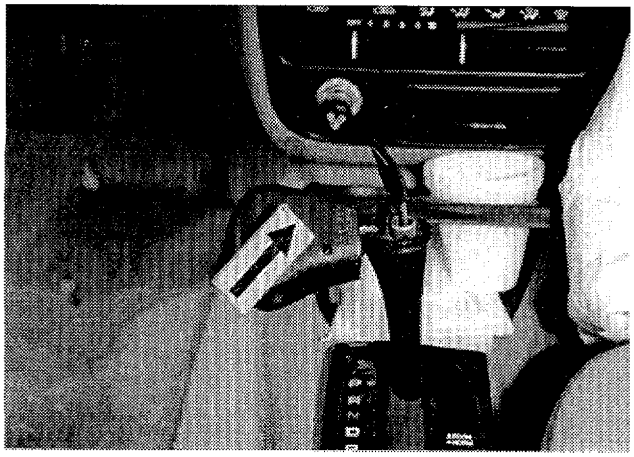

Figure 6. Broken transmission shift lever.

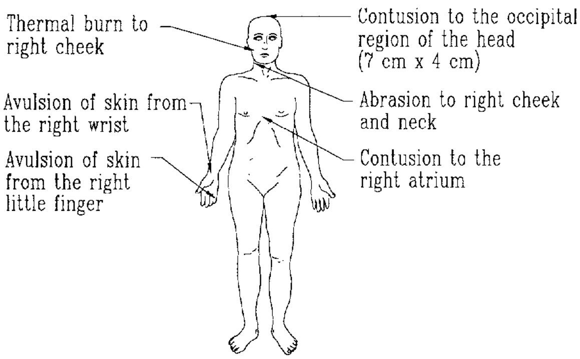

Figure 7. Soft Tissue Injuries.

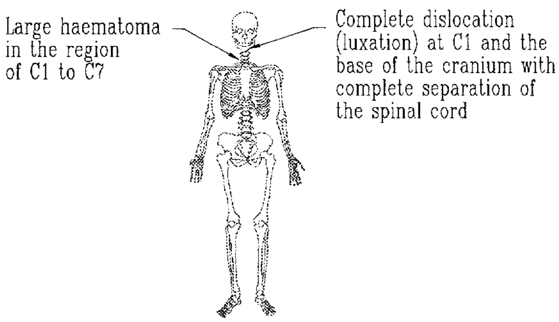

Figure 8. Skeletal Injuries.

RECONSTRUCTION METHODOLOGY

The interaction between the passenger air bag and the child was reconstructed using a series of static air bag deployments in a custom test fixture. The tests were performed with an instrumented, 6-year-old ATD.

The test fixture incorporated a dashboard, an automatic transmission shift lever, and a seat from an exemplar vehicle. The generic windshield, forming part of the test fixture, and all the above components, were adjusted to correspond with dimensions taken from an exemplar vehicle.

In the tests, a seat belt was not used because in the actual collision the child was only wearing the lap belt and, since the child was determined to be on the forward edge of the seat cushion, with the belt extended, it was felt that the lap belt had minimal effect on the occupant kinematics.

The known injuries to the child, the observed damage to the vehicle interior, and the description of the pre-crash events from the driver were all used to approximate the position of the child prior to air bag deployment.

As noted above, green transfers from the child's jacket were observed, primarily on the left side and the top portion of the air bag. These witness marks, the abrasions to the right side of the child's neck, and the thermal burn to his right cheek, were indicative of the child's head being in close proximity to the air bag's vent. The large contusion to the occipital region of his head corresponded to contact with the transmission shift lever.

It was felt that the avulsion of skin from the wrist and little finger on his right hand were consistent with contact by the air bag cover. The driver reported that the child was leaning forward, towards the centre console, either to play with the radio controls, or obtain some candy from a cup in the cup-holder. A child of similar age was placed in this scenario. It was observed that when the child moved forward in the described manner, it was natural for him to support himself with his left hand on the seat cushion, and to use his right hand to obtain the object. Pre-impact braking in the real-world collision may well have caused the actual right-front passenger to support himself with his right hand against the upper dashboard and air bag module.

Test Series

The broken gear shift lever was the critical occupant contact point, demonstrating that the child's head had been propelled both rearwards, and down towards the centre console. Consequently, achieving head contact with the transmission shift lever was a major goal of the reconstruction. Static testing revealed that minor changes in the position of the dummy had considerable effect on its kinematics. Four passenger air bags were deployed before successful contact between the dummy's head and the lever was achieved. These tests were done to establish the position of the dummy prior to performing a final dynamic test. A description of each of the four static tests, and the results of each test are as follows:

Test 1 - The dummy was positioned on the front part of the seat cushion, leaning forward, with the head adjacent to, but not touching the right side of the centre console. The right arm was extended, with the hand lightly taped to the leading edge of the air bag cover, just to the right of the cover's centreline. The left arm was beside the thorax, and the forearm was on the seat cushion.

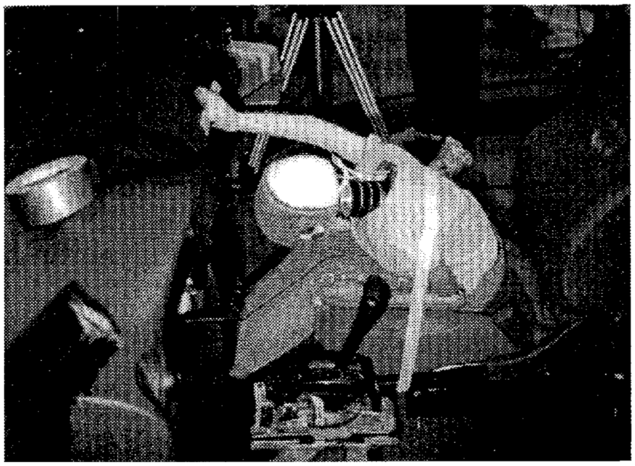

Figure 9. Dummy position in Test 1.

The air bag deployed around the extended arm, propelling the arm rearwards. In the process, the hand detached from the arm. The air bag engaged the dummy's head and thorax and drove the dummy rearwards into the seatback. The head passed well over the top of the gearshift lever.

Test 2 - The dummy was positioned on the front part of the seat cushion, leaning forward with the head contacting the right side of the centre console.

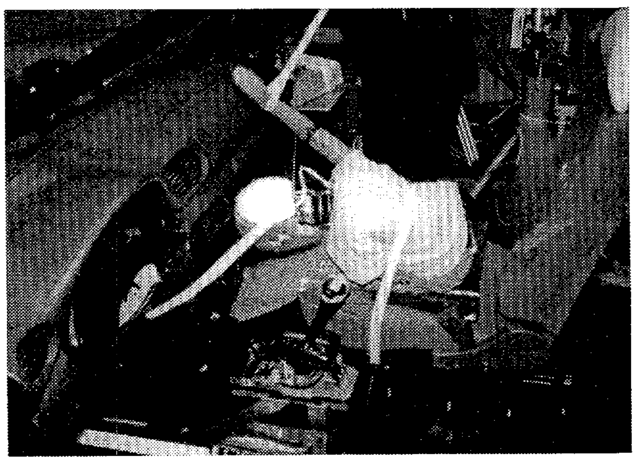

Figure 10. Dummy position in Test 2.

The head was placed slightly lower than in Test 1. The right arm was extended, and the right hand was suspended a few inches away from the centre of the air bag cover. The left arm was beside the thorax with the forearm on the seat cushion.

The air bag deployed over the dummy's right shoulder, around the extended arm and, as it reached maximum inflation, it propelled the arm rearward. The air bag engaged the upper thorax and sent the dummy rearward. Although there was contact to the dummy's head, it still travelled well above the gearshift lever.

Test 3 - The first two tests revealed that the interaction between the air bag and the dummy was missing a downward component.

For the next test the dummy was positioned on the front part of the seat cushion, leaning forward, with the thorax rotated towards the right. The head was placed lower, between the lever and the centre console, but not touching the centre console. The right hand and forearm were on the dummy's lap, and the left arm was beside the thorax with the forearm on the seat cushion.

The air bag now deployed essentially over the top of the dummy, with little contact to the dummy.

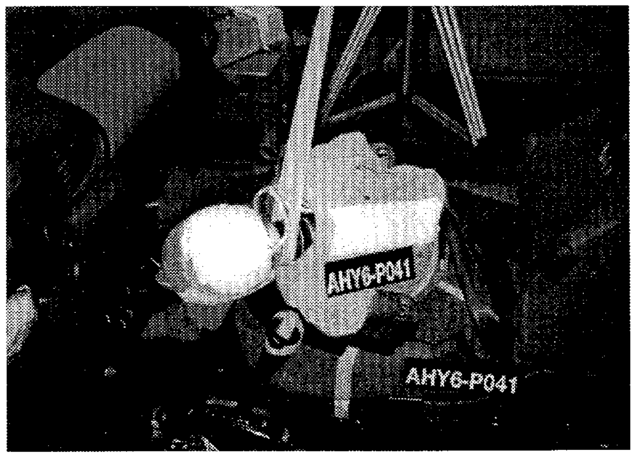

Figure 11. Dummy position in Test 3.

From this test it was concluded that the right arm was a critical component in the deployment characteristics of the air bag. The arm provided an obstruction which altered the inflation of the fabric envelope, and consequently substantially influenced the kinematics of the dummy.

Test 4 - The dummy was placed in a forward leaning position, similar to Test 2 with the head touching the right side of the centre console. The right arm was now extended, with the hand on the leading edge of the air bag cover. The hand was placed on the right side of the cover. The left hand was placed on the seat cushion, with the elbow bent at 90 degrees.

The air bag initially deployed between the right arm and the neck of the dummy. The head was in the area of the lower left corner of the air bag and, as the air bag reached maximum inflation, it drove the head down and rearwards. In this test, the occipital region of the dummy's head struck the end of the gearshift lever, fracturing this component.

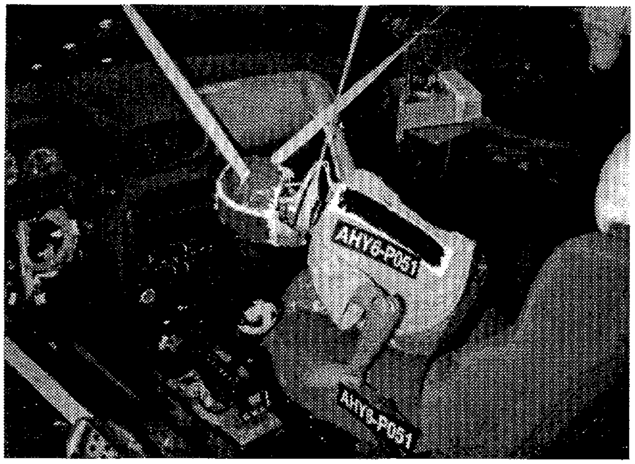

Figure 12. Dummy position in Test 4.

Dynamic Test

A dynamic reconstruction of the interaction between the airbag and the child was also performed. The dummy was placed in the same position as Test 4. In the dynamic test the lap belt was positioned around the dummy's hips, with the torso belt behind the back, to simulate the actual collision situation. The vehicle was run into a fixed barrier at a speed of 26 km/h.

At impact, the dummy moved forward, loading the lap belt. The airbag deployed and the dummy's right arm was propelled rearward. The airbag started to fill out above the head and right shoulder of the dummy; however, some of the air bag fabric inflated lower down. Consequently, the head of the dummy was located more towards the middle of the left side of the air bag, rather than at the lower left corner of the bag as was observed in Test 4. Rather than the head being driven rearwards and down, it was projected rearwards and more laterally. Although the dummy's head travelled close to the gearshift lever, it did not make contact. In fact, the dummy's kinematics were comparable to Test 2.

The dynamic test confirmed that the positioning of the dummy was critical. The static testing reconstructed the position of the child at deployment, the occupant kinematics, and injury mechanism. Positioning the dummy in a dynamic environment, and trying to account for vehicle deceleration, in order to produce the desired occupant kinematics, is extremely difficult when the initial tolerances on positioning are small.

DATA ANALYSIS

ATD Kinematics

Motion analysis was conducted on high-speed film and video recordings made of the above-noted full-scale test. Detailed examination of these records, illustrates an exceedingly complex head-neck-torso motion sequence. In broad terms, the child ATD motion is as follows:

- At t=29 ms, the instant that the air bag first begins to deploy, the ATD neck is flexed forward and slightly to the left.
- At t=37 ms, the bag completely fills the space between the right side of the head and the top of the right shoulder. It is beginning to engage the top of the chest.
- At t=42 ms, the bag completely envelopes the right side of the head and, presumably, the neck. The neck has begun to flex to the left.
- At t=52 ms, the head is flexed to the left to the maximum. At this time, the head/neck, which is also twisting counterclockwise, begins to go into extension as the bag continues to unfurl under the chin.
- At t=59 ms, the neck is extended to its maximum and the head begins to rotate clockwise. The torso also begins to rotate clockwise (but at a lower speed) due to the bag interacting with the right upper chest and shoulder of the ATD. At this point, the bag appears to fully engage the chin of the ATD and causes the head and neck to continue twisting. As the torso is accelerated, the head and neck begin to return to a seemingly neutral alignment with the torso.
- At t=90 ms, the ATD has rotated clockwise fully 90 degrees from its original position and the left side of the air bag appears to interact with the front of the ATD in much the same way that a non-out-of-position occupant would with a frontal air bag deployment. The neck is no longer extended and is about to go into flexion. The ATD then disengages from the deflating air bag and is propelled toward the left passenger compartment.

Instrumentation

Load cells at the top and bottom of the neck provided axial, lateral and fore-aft shear forces, as well as bending moments in all three planes, at both the head/neck and neck/thorax junctions. Though the primary injuries of interest are at the top of the cervical spine, consideration of the forces and moments at the bottom of the neck may also be helpful in understanding the loading mechanisms.

It will be noted at the outset that this series of measurements predicts a fatal neck injury by virtually every conceivable mechanism. Commonly accepted tolerance data are so far exceeded for every mode of injury, except compression, that the present data will not be able to refine further the numerical values of neck injury assessment criteria.

A recent study, designed to develop child injury protection reference values (Klinich et al, 1996), proposed the following function to take into account axial loading and bending of the neck.

$$N_{T;F,E} = \frac{(F_x^2 + F_z^2)^{1/2}}{F_c} + \frac{M_y}{M_{c;F,E}}$$

where:

- N_{TF} is the neck tension-flexion index,
- N_{TE} is the neck tension-extension index,
- $F_{x,z}$ are the forces in the x and z directions,
- M_y is the bending moment in the y direction,
- F_c is the critical force value, 3000 N for the 6-year old dummy,
- M_{cF} is the critical flexion moment value, 70 Nm for the 6-year old dummy,
- M_{cE} is the critical extension moment value, -35 Nm for the 6-year old dummy.

In order to comply with these protection criteria, the value of the weighted neck injury assessment functions should not exceed 1.0.

The neck tension-extension index (N_{TE}) for this test case is equal to 1.56 at the upper load cell and 2.72 at the lower load cell.

The neck tension-flexion index (N_{TF}) is 1.78 at the upper load cell and 1.20 at the lower load cell.

It is important to note that these neck protection reference functions do not include lateral bending moments, which, in the present case, are the most significant of all the bending moments.

In terms of the expected mechanism of injury, one should also not disregard the axial twisting moments. Though numerically smaller than any of the other directions, these values are consistent with estimates of the torsional loading associated with serious neck injury. Certainly if combined with the other bending moments in the fashion proposed for extension or flexion loading, the effects would be dramatic.

Observations and Discussion

To more fully understand the loading mechanisms to the child ATD neck, the loads at both the upper and lower load cell locations, and the timing or phasing of the various loads and moments were considered. Examination of the data traces reveals some interesting features of this air bag induced loading:

1. There is a direct correlation, both in terms of magnitude and curve shape, between head a_z and F_z. The correlation at the upper load cell reflects the rigid connection between the head and load cell. The correlation to the lower load cell is due to the relatively rigid coupling between the head and chest through the neck by way of a metal cable.
2. Maximum neck load is in the z direction and occurs after the head has extended rearward about as far as it's going to go. At this point, the steel cable is producing high resisting loads and, because of its strength, retains the structural integrity of the neck.
3. Maximum head acceleration is in the y direction and exceeds the limit for low risk of brain injury. The pulse maximum is over 110g and the duration is about 10 ms. This is very much a "slap". Disengagement with the side of the head occurs fairly quickly. The head accelerates in the positive z direction (i.e. downward) as the head is rotated and the bag continues to engage the ATD chin.
4. No obvious correlation exists between head acceleration and the two shear components, F_x and F_y, at either the upper or lower neck load cell positions. However, shear forces at the upper location persist long after the head has ceased to be accelerated by the air bag. The reaction loads may not correlate because there may be some direct loading on the neck assembly by the air bag. More likely, these loads are associated with the head, now moving laterally relative to the neck axis, (having been accelerated by, but no longer in contact with, the air bag), deforming the neck of the ATD.
5. F_y is significantly higher at the lower load cell than at the upper. This could reflect that the resisting forces are associated with the additional mass of the neck, or that there may be some direct loading by the bag. Algorithms to ascertain the extent of each could be developed.
6. F_x is significantly higher at the upper load cell than at the lower. This probably reflects that the reaction load here tracks a_x while the lower load cell "sees" relatively little fore-aft loading until the head actually starts to move.
7. For the first 10 ms of neck loading, M_x is negative at the upper load cell while being positive at the lower. At 45 ms, the moments at both locations become positive and remain so till 75 ms. The initial reversal suggests the neck is bending in an "S" shape. This suggests that the head is initially translating to the left, on top of the neck, as a result of the loading to the head. This appears consistent with the line of force being below the centre of gravity of the head.
8. The maximum value of M_x at the lower load cell is twice as high as at the upper. There is no obvious explanation for this observation. However, it appears

that the head may be partially supported by the upper shoulder of the dummy at maximum extension. This would have the effect of transferring some of the resisting moment to an external reaction load. The lower neck is perhaps not benefiting from any external support.

9. The maximum values of M_y at the upper and lower locations are virtually the same but the directions are opposite and out of phase. The upper bending moment, a flexion moment, is maximum at about 48 ms. At this time the lower moment is virtually zero. At 60 ms, the lower neck exhibits maximum extension moment while the moment at the upper location is near zero. As in the case of M_x, the neck is adopting a curious shape. Initially, the neck is straight and the head flexed at the head/neck region. Later, the upper part of the neck returns to an essentially neutral orientation, but the lower neck is bent rearwards.
10. The bending moments reach their maximum value well after the head has stopped accelerating. For example, at the upper neck location, M_x is at a maximum (left lateral flexion), some 20 ms after a_y (to the left) has subsided. As with the shear forces, these moments persist because, though the head is not accelerating (substantially), it is moving, and the neck must retain the head to the torso, which is being accelerated by the neck.

CONCLUSIONS

Based on the static and dynamic reconstruction testing, and the injuries indicated in the autopsy, the following conclusions are drawn:

1. This fatal neck injury was due to the structural failure of the atlanto-occipital junction because the ligament structure, responsible for retaining the base of the head to the top of the neck, failed. The head, no longer retained, exposed the spinal cord and brain stem, as well as the surrounding muscle and soft tissue, to direct tensile loading. Being unable to sustain significant tensile stress, the stem/cord tore apart.
2. The precise mechanism is somewhat unclear because not all the injuries are described in the autopsy report with adequate detail. Also, it is obviously not possible to determine the sequence of the injuries from the autopsy report, only the actually injuries at the end of the process. The ability of the ATD to respond in a biofidelic manner is not clear. Notwithstanding these shortcomings, an injury mechanism is postulated:
3. The victim's head was rapidly pulled from the top of his neck as a result of the expanding air bag partially enveloping and accelerating his head.
4. The neck structure was subjected to axial loading, bending, and twisting by the air bag.
5. Tensile loading destroyed the ligament structure responsible for retaining the head on the top of the neck. It was both avulsed from the base of the skull and was ruptured around the top two vertebra. The head of the victim thereafter was retained only by the surrounding muscle and soft tissue, which was also partially ruptured in the process. The spinal cord was extruded and stretched to the point of complete rupture in the process.
6. The rapidity of the event is consistent with the absence of ligament failure around the lower cervical spine.
7. It is likely that the victim's head was separated from the torso by many centimetres. This motion cannot be replicated by the ATD because of the strong, stiff central cable running through the ATD neck.
8. The biofidelity of the ATD neck is dubious for all kinds of direct loading to the head (and/or torso) but especially so in the z direction. Certainly the measured high axial loads are attributable to the high stiffness in this direction. Because of this, head acceleration in the z direction will also be artificially high. While one would hope to be able to use the artificially high neck loads as part of an ATD neck protection criterion function, this study suggests that positive values of a_z should not be included in the calculation of resultant head acceleration.
9. It is expected that the axial neck loads experienced by a child would be of vastly lower magnitude and of longer duration. The skull-cervical spine load would persist only until the upper cervical structure failed. The ATD load, on the other hand, (whose neck does not fail), would continue increasing even further. Without stating the obvious, since one cannot know at what load or time the actual neck would have failed, one cannot expect to correlate the actual injury with the maximum ATD neck axial load measured during such a test as this.
10. The mechanical replication at the top and bottom of the cervical spine is poor. The ATD cannot articulate the way a human spine does, thus possible correlation with measured shear loading and bending moments, is dubious. Though it is acknowledged that the actual forces and moments may be different due to what are basically stiffness effects, the real issue is that the head and neck may not be able to orient themselves in a way that the induced loading even begins to approximate the expected reality of an air bag. The significance of this point depends, obviously, on when during the event the actual ligament injury occurs. If it happens very early, the absence of good motion replication may be less important. In cases of excessive overloading, such as the present, perhaps

this factor is less important. In cases where one is attempting to reproduce threshold injury situations, it will be more so.

11. Maximum loading of the neck occurs after the head has been accelerated by the air bag. The ATD head, moving away from the torso, but connected to it by the neck, places the neck under loading as it "tries" to further accelerate the torso.
12. Measured neck twisting moments are numerically smaller than those for flexion and extension. However, the injury threshold moment for twisting is lower than for flexion or extension and thus should not be disregarded in assessing the neck injury potential associated with a particular ATD test.

ACKNOWLEDGMENTS AND DISCLAIMER

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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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