THE COMING REVOLUTION IN AIRBAG TECHNOLOGY

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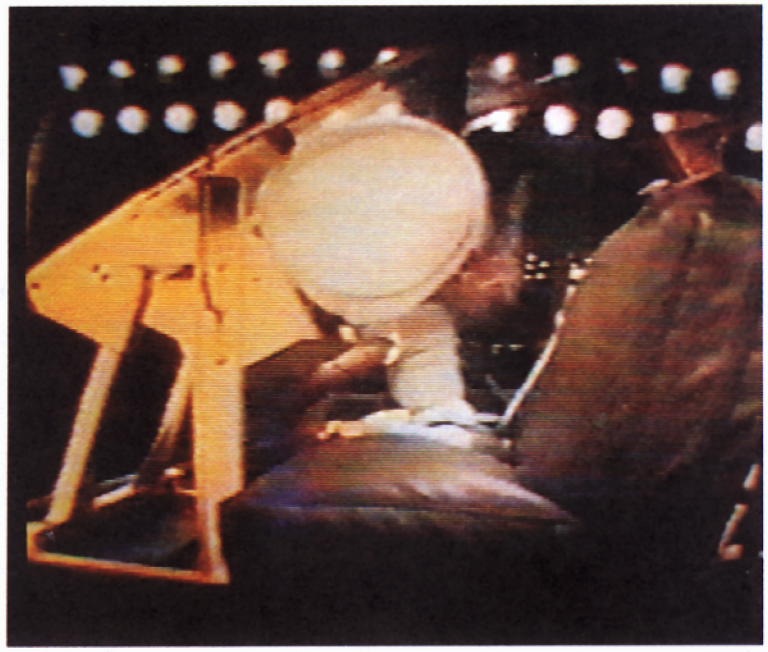

ABSTRACT

There are now tens of millions of airbag-equipped vehicles on the highways. In vehicle collision accidents, thousands of lives have been saved, and tens of thousands of potentially severe injuries have been reduced. Yet, there are also injuries caused by various airbag systems, especially in low-speed to moderate-speed accidents in which no other significant injuries would likely have been caused.

Short-stature drivers and children passengers in the right-front seat, have been documented as the most vulnerable to airbag-caused severe to fatal injuries. There have therefore been incentives for motor vehicle manufacturers, airbag system manufacturers, and government agencies to move ahead in the development and implementation of safer airbag technology. This report examines the concepts, developments, and directions for airbag safety innovations.

A typical present-day airbag system is comprised of the basic elements of:
(a) crash sensors to detect the sufficient deceleration that indicates a frontal collision is likely beginning, (b) a gas generator that instantaneously produces a sufficently high volume of gas, (c) a stored airbag in the center of the steering wheel and in the instrument panel that will become fully inflated in about 30-to-40 milliseconds, and (d) a diagnostic module that can monitor and validate the readiness of all the sysytem's component.

The criteria for airbags is no longer to simply offer automatic protection for the driver and front seat occupants in frontal crashes. More stringent requirements reflect the public's understandable concern after reports of airbag-caused fatal injuries to shorter drivers and children passengers. The airbag also must not create a risk nor cause injury to the shorter driver or others who may be too close to the stored airbag, such as with an unbelted or belted person moving forward during pre-crash braking. Nor should the airbag cause injury to small children passengers, who may be in a child safety seat or somewhat out of position (e.g., unbelted and leaning closer to the stowed airbag).

This may require airbag systems that have sensors or other means to detect the potentially adverse situation, and then restrict the particular airbag from deploying. This will also require automakers to verify compliance to test procedures that no longer focus on the 50th-percentile adult male test dummy, but will also include short-stature

female drivers and child test dummies as well. Larger, tall test dummies should also be included in a more comprehensive test matrix of various individual sizes, weights, and seating positions.

While initial airbag systems have concerned occupant protection in frontal crashes, a second wave of airbag systems concerns occupant protection in side impact crashes and vehicle rollover accidents. Various designs offer protection for the torso, or for both the torso and also higher at the occupant's head level.

AIRBAG FATALITIES TO CHILDREN

A major airbag problem concerns the continuing epidemic of severe to fatal injuries to infants and young children who are in the right-front passenger seat of a vehicle equipped with a passenger-side airbag. At a National Transportation Safety Board (NTSB) hearing in September 1996, it was noted that there were 26 documented cases since 1993 in which infants and young children had been killed by passenger-side airbags in collision accidents that they otherwise would have likely survived with either minimal or no injuries. Many of the collisions were at very low speeds, in the 8 to 20 mph range. The tragic epidemic continues at the rate of one additional child fatality per week.

The evaluation of why children were being killed by airbags focuses on a few key issues, some behavioral and some technical. Though recommendations were typically expressed that children should always or preferably ride in the back seat, it was often difficult for the parent to place the infant where he or she was not immediately accessible next to them. As for young children, ages 5 to 12 years or so, it's understandable that parents would allow them to ride in the right-front seat, since the lap and shoulder belt appeared to be fit well enough... and they'd also enjoy *the added protection* of the passenger-side airbag, or so it logically seemed.

The passenger-side airbag bursts or explodes from the instrument panel at speeds from about 90 miles per hour to 210 miles per hour. The rapidly-inflating airbag can impact the passenger with a force as high as about 2,000 pounds. As it inflates, the airbag's maximum distance extending horizontally rearward from the instrument panel can be as much as 18 to 24 inches toward the child or safety seat.

Some airbags are stored in the front face of the instrument panel, and inflate *horizontally* directly toward the passenger. If it involves a small child or a rear-facing infant seat, the horizontal deployment airbag is aimed directly at the head of the small child or directly into the infant seat. Other airbag modules are located on the upper surface atop the instrument panel, and initially inflate *vertically* upward and then wrap over toward the seated passenger.

From evaluating the prior research and also the current knowledge about which *specific* airbag designs are causing fatal injuries to children passengers, it appears that some of the horizontally deploying airbag designs (e.g., Chrysler, Ford, GM) are the more injurious ones, while the top-mounted vertically deploying airbag designs (e.g., Honda, Toyota, Subaru) are significantly safer and non-lethal.

If pre-crash braking is involved, the child may also be moving toward the instrument panel. If the right-front passenger seat is not adjusted to its maximum rearward position, the passenger's closer proximity to the inflating airbag can lead to a greater risk of airbag-caused injury. Even if the child is wearing the lap-and-shoulder belt, a combination of poor belt performance (too much slack, slow lockup response), and possible forward adjustment of the seat, the airbag could nonetheless still cause a severe punch to the child. Yet, in many accidents, the airbag can also offer significant protection for the child passenger on the front seat.

TOWARD A SOLUTION: "SMART" AIRBAGS

The proposed solutions focus on what is called a *"smart airbag"* system, where the airbag inflation pressure, or even whether or not to activate, are automatically responsive or proportional to the speed of the crash and the weight of the person (child or adult) on the seat.

Some proposed "smart airbag" designs include occupant weight sensors in the seat cushion to detect whether the right-front seat is occupied, and by how much weight (child, small adult, large adult). Infrared detectors can also determine whether or not there's a child safety seat present. If the sensors detect a potentially dangerous situation, such as the close proximity of a rear-facing child safety seat, the airbag is disengaged and will not actuate in a crash.

Alternative proposals describe an airbag system able to inflate the airbag in proportion to the severity of the crash... with a ***"softer"*** inflation pressure for lower speed crashes, and a ***"firmer"*** bag for higher speed crashes. Some of GM's early-1970's dynamic sled tests and crash test studies using child dummies and live baboons indicated changes needed to reduce the potential injury to children. These improvements were incorporated in the GM ***"Air Cushion Restraint System"*** (ACRS) implemented in the 1973 Chevy Impala test fleet, making them the world's first cars with a "smart" airbag system.

Another desirable upgrade would be the development and mass implementation of *"smart"* airbag systems that can detect when a child or rear-facing child seat is in proximity to the passenger airbag, and cause softer inflation pressures in such instances, especially in low and moderate speed crashes. A parallel feature would sense when the seatbelt is being worn by the passenger (similar to a feature in some Mercedes airbag systems, which raises the airbag actuation speed threshold when the driver is belted).

As discussed above, it is also important to locate the stored airbag module in such a location that the initial burst-out forces will not be concentrated directly toward the head or neck of a seated child or small adult. Thus, the top-mounted vertically-deploying passenger airbags are a safer embodiment than the horizontally-deploying airbags that are located in the front face of the instrument panel.

THE 1973 GM DUAL-MODE AIRBAG... AND CHILDREN

The very first production airbag system, developed by General Motors and utilized initially in a test fleet of 1,000 specially-modified 1973 Chevy Impala 4-door sedans, did in fact have a "smart" two-stage inflation pressure. GM then offered their two-stage airbag system as a $235 extra-cost option in some models of the 1974-75-76 Oldsmobile, Buick, and Cadillac.

"Low speed detectors are designed to activate the total system in a frontal type collision with an immovable object, such as a wall, at about 11 m.p.h. When striking a comparable parked vehicle (which will move or crush), the low speed detector will activate the system at about 22 m.p.h."

"In more severe accidents the high speed detector will more firmly inflate the passenger system at about 18 m.p.h. when striking an immovable object, and about 36 m.p.h. when impacting a comparable parked car."

General Motors early-1970's concern about the airbag's deployment effects on children was described in a 1974 GM report:

"... work utilizing live baboons in laboratory experiments indicated a potential inflation hazard to small children who might be out of the normally seated position. The result of this program also stimulated the redesign program for the passenger restraint system."

"The possible inflation hazard experienced with the first generation design was reduced by providing dual sensing of impact severity and control of cushion inflation. During impacts of low severity, a low inflation of the cushion would be used. For high severity impacts, a faster deployment of the air cushion was provided."

"An additional series of tests... indicated the second generation air cushion restraint would reasonably control the inflation hazard to small children."

Thus, the 1973-1976 GM airbag system already had the safety benefits of a softer bag for lower speed crashes, and a firmer bag for more severe crashes. This is a 20-year-old feature that will soon likely be "re-invented" in order to help solve the dilemma of airbags that can and do kill children in the right-front passenger seat. The airbag's explosive dangers to children, described mostly as "out of position" children, was discussed in the '70's and '80's when some automakers were voicing concerns about airbags.

When it came time to implement airbags in the 1988 to 1996 era, most automakers did not include features that would make airbag inflation pressures proportional to the severity of the crash and the weight of the person on the seat. Some automakers made the crash sensor threshold or actuation speed very low, with a trigger speed as low as 8-to-12 miles per hour BEV (Barrier Equivalent Velocity).

AIRBAG INJURIES TO SHORT WOMEN DRIVERS

Short adult drivers, especially women, have been severely and fatally injured by the explosive force of a driver's airbag... even in low to moderate speed crashes. Because of their short stature, from perhaps 4'10'' to around 5'4", shorter drivers need to adjust their seat virtually to its full forward position. This places their chest and head in close proximity to the steering wheel. In the center hub of that steering wheel is the stored airbag, ready to inflate in a frontal impact. The powerful and instantaneous inflation can move the unfolding airbag toward the driver at 120 to 200 miles per hour, and generate a force of 2,000 pounds.

Some of the initial accident case examples concerned shorter women drivers, sitting very close to the steering wheel, who were fatally injured when the explosive force of the airbag fractured their ribs, which punctured and tore their aorta. The crashes were moderate in nature, and the airbag was the needless cause of death in what would have been a survivable collision. Some of the women were shorter, older, and more frail... making them more susceptible to the airbag inflation forces breaking their ribs, tearing their aorta, and causing fatal injuries.

The generally accepted precaution or recommendation, by NHTSA and most automakers, is for the driver to adjust their position so there is at least 10 inches of distance between their sternum and the center of the steering wheel. The vast majority of short-stature drivers should be able to position the seat and backrest, and the tilt and telescope steering wheel if so equipped, so that the recommended distance of at least 10 inches is attainable, without also compromising safe pedal reach and safe visibility.

HOW AND WHY AIRBAG HAZARDS OCCURRED

How could such a prominent safety technology as airbags been compromised, leading to needless deaths and injuries ? Airbags are not a new development, despite the general public perception that airbags are a technology of the '90's. In fact, the development of airbags goes back to the '50's and '60's, when the earliest dynamic sled tests and car crash tests by GM and Ford and Eaton Corporation showed their great promise to reduce traumatic injuries in collision accidents.

There was anticipation in the early-'70's that airbags would soon be installed. NHTSA had initiated rule-making, and the car companies in the U.S., Europe, and Japan were all developing airbag systems for their vehicles. However, top officials from Ford and GM and Chrysler went to the White House in 1971, and urged President Nixon to delay the then-pending auto safety standards, including the requirement for airbags.

The pending 1970's requirement for airbags was politically shelved, and languished in limbo into the mid-1980's. There was nothing preventing car companies from installing airbags on their own. After a United States Supreme Court decision in 1983 forced NHTSA to re-examine their latest cancellation, the rulemaking process began again. NHTSA and DOT responded with a 1984 plan to link mandatory buckle-up laws to a decision about requiring airbags. Without waiting for a NHTSA mandate, Mercedes introduced airbags in some models in 1984, and Ford offered a driver airbag option in the 1985 Tempo.

In 1988, Chrysler began to promote airbags as a standard feature in most of their cars. This was a major reversal by Chrysler CEO Lee Iacocca, who had opposed airbags for years... including his criticisms made in 1971 in the Oval Office to President Richard Nixon. In his 1984 autobiography, Iacocca was highly critical of airbags, even granting *"they'll work in 99.99 percent of cases"*. He feared the powerfully explosive airbags *"can also be dangerous"* and would also cause injury and death in some cases... and that airbags would therefore create a liability nightmare for the car companies.

In the 1989-1993 era, the news media began to report and dramatically illustrate that lives were being saved in head-on collisions, *thanks to airbags*, and the public demand for airbags began to gather momentum. With the simultaneous pressure from both a 1991 Congressional mandate and the upgraded Federal Standard, the race to install airbags swept across the auto industry through the 1990's.

Airbags are a well-proven live-saving and injury-reduction technology. Thousands of people have survived crashes, due to airbags, in which they otherwise would have likely died. The current estimate is that at least 500 vehicle occupants are saved from fatality injuries per year. As each year brings an additional 14 million airbag equipped vehicles onto U.S. roads, the value of airbags to prevent severe to fatal injuries will obviously increase the number of survivors.

Yet, the advent of millions of airbag-equipped cars, pickups, and vans has led to a combination of circumstances and accidents in which the airbag itself was the cause of the fatality. Examples have included short women drivers, perhaps somewhat slight of stature, sitting very close to the steering wheel, involved in 15 to-20 mph frontal collisions. Other examples include young children, such as a 7-year-old girl, safety-belted on the passenger seat of a Chrysler minivan, in a 10 mph frontal crash, Another concerns an infant in a forward-facing child safety seat, killed by the airbag in a minor parking lot accident.

OVERVIEW OF AIRBAG COMPROMISES AND OMISSIONS

Many of the fatal airbag accidents have been evaluated. The history of how airbags have been an on-again, off-again, on-again safety technology has been reviewed. The roles of the auto industry and the federal auto safety agency have been considered. Amidst the historical and present wealth of information, here's an overview of some basic compromises, omissions, and misjudgments that have caused life-saving airbag systems to also be occasionally hazardous to children passengers and short women drivers.

Failure to design and test airbags for smaller women and children, instead of only for an "average man". When airbags were required to comply with FMVSS 208, the basic test was and is a full-front impact of the vehicle into the concrete barrier at a speed up to 30 miles per hour, with injury limits specified for the head and chest of an unbelted 50th-percentile adult male dummy, about 5'9" tall and weighing 167 lbs. Even though the automakers and NHTSA could have *also* specified a range of test dummies, including shorter women dummies and child dummies, the desire for simplicity and economy prompted only a single crash test using just that 50th-percentile *"average man"*. And the driver's seat was adjusted accordingly.

Failure to set the airbag's actuation threshold speed higher, rather than as low as each vehicle manufacturer wants... sometimes too low. There was no actuation threshold speed specified below which the airbag should not inflate. At an auto manufacturer's discretion, the threshold speed could be as low as 8 to 10 miles per hour... or as high as 16 to 18 miles per hour In some cars, the crash sensor, which releases a magnetically-held steel ball, would therefore be very sensitive to low-speed deceleration.

Failure to have multiple inflation pressures, rather than just a single-mode high inflation pressure that's too high for the less severe crashes. Virtually all manufacturers adopted an airbag system that used sodium azide pellets to instantaneously generate a large amount of nitrogen gas that would immediately fill the stored airbag and burst it through its cover panel into a large, inflated, rigid pillow. The airbag would then deflate through side vents as the occupant loaded into the cushion. But once the ignition process began, the entire amount of sodium azide was activated, meaning the inflation pressure would always be the same... rather than a "softer" inflation for lower speed crashes, and a "firmer" inflation for higher speed crashes.

Failure to use airbag tethers and shapes that would ensure a greater distance between the inflating airbag and the driver or passenger. The speed of the inflating airbag is from 90 to 210 miles per hour, and can generate a force of 2,000 pounds. Tether straps are used inside the airbag to help shape the inflating bag and reduce the distance that the airbag inflates from its stowed position within the steering wheel hub and the instrument panel. Tethered driver airbag maximum distances from the instrument panel range from 12 to 15 inches, while untethered driver airbags range from 17 to 20 inches or more and are thus can dangerously impact into the chest and head of the short woman as the airbag explosively inflates.

A similar situation exists for the larger-size untethered passenger-side airbag... causing the airbag to explosively inflate and impact into the head of the child, causing severe to fatal brain and neck trauma. It is analogously important to consider the merits of tethers to control the inflation shape and excursion distance of the passenger airbag. The use of tethers would help make the passenger airbag inflate as a flatter pillow, rather than a rounded basketball shape, and would reduce the distance of the inflated airbag from the passenger.

Failure to include a "seatbelt-in-use" detector switch to raise the airbag actuation threshold to a higher speed. If the driver is wearing his or her lap-and-shoulder belt, then there's less need for the "supplemental" airbag to inflate, especially in low to moderate speed crashes. But some automakers have provided seatbelts that fit poorly, or that have too much slack, or that don't lock-up quickly enough in the crash. And most automakers don't want the extra cost of using a seatbelt detector that will raise the airbag's actuation threshold if it detects the driver is in fact wearing the seatbelt... such as from 12 mph if you're unbelted, raised to 18 mph if you're belted.

Failure to provide the safer seatbelt pre-tensioners to snug the belt at the start of a crash. Seatbelt pre-tensioners are devices that automatically take up any seatbelt slack, thereby snugging the lap belt and shoulder belt to the wearer's body at the start of a crash. Snug fitting belts serve as a more effective restraint, keep the occupant from excessive forward movement, and prevent a looser-fitting shoulder belt from slipping off the occupant's shoulder. Most seatbelt pre-tensioner systems also use a force-limiter feature that alleviates excessive loads on the occupant's body during the crash. Most European cars and upper-scale Japanese cars use seatbelt pre-tensioners. The only American brand that presently includes pre-tensioners is the new 1997 Cadillac Catera, which is essentially a restyled Opel that's imported from Germany.

Failure to recess the stored airbag a bit deeper, to allow more distance between the inflating airbag and the shorter driver. Recessing the stored airbag deeper below the plane of the steering wheel creates more distance between the explosively-inflating airbag and the driver, especially the shorter driver who sits very close to the steering wheel.

Failure to provide or offer a telescoping adjustment for the steering wheel. Include an adjustable telescoping steering wheel as a standard feature, so shorter drivers can adjust the steering wheel to be further away from themselves. This would create a safer distance between the explosively inflating airbag and the driver. Many steering wheels have a tilt feature, but not an ability for fore-and-aft telescoping as well.

Failure to provide or offer an adjustable pedal platform. Include an adjustable pedal platform for the accelerator and brake pedals, to accommodate shorter drivers, and thereby reduce their need to adjust the driver's seat to a full forward position. GM was rumored to have designed such a movable pedal platform, and was going to introduce it as an optional feature in some early-1970's Pontiac or Olds models. It may have been intended to help the airbag problem for shorter drivers. When GM abandoned its 1970's-era airbag program (after building about 11,000 cars in 1973-1976 with airbags for the driver and both front passengers.), this adjustable pedal platform feature never surfaced again. Pedal extenders can also help make the brake and accelerator more accessible to shorter drivers. Pedal extenders are also available at some of the companies that modify vehicles for handicapped persons.

Failure to provide sufficient warnings in highly-visible labels. Most vehicles lack the prominent display of highly-visible warning labels to alert the driver and passenger of the problems of sitting too close to the stored airbag, and of the need to always wear the lap-and-shoulder belt and keep it snug, and also to include the above-noted concerns about infants and children.

TEMPORARY MODIFICATIONS TO FMVSS 208

In efforts to alleviate the pending airbag problems, some auto companies urged NHTSA to modify the applicable safety standard, FMVSS 208. Ford Motor Company wanted the compliance crash speed reduced down from 30 mph to 25 mph, and also to allow the acceptance of chest injury forces to go from 60g's up to 80 g's. This would allow the automakers and airbag system suppliers to "depower" the airbags to make them 20-to-35-percent less forceful when they inflate. This could likely be accomplished by simply using less sodium azide propellant in the inflator cannister, for example.

General Motors also urged that a dynamic sled test, simulating a 30 mph vehicle-into-barrier crash test, be utilized as the only compliance test. Therefore, as Ford and GM urged, the lowered test requirements and more-permissive injury criteria would allow them to use an airbag that deploys with less force, which would supposedly reduce the injury potential to children.

Yet, reducing that particular FMVSS 208 crash test requirement may ***increase*** the injury potential for the larger adults. And using a sled test instead of an actual vehicle crash test, takes away the reality of evaluating the total vehicle's crashworthiness performance (e.g., how the windshield pillar moves toward the driver's head, or how the floorpan buckles at the driver's feet, or how the steering column re-orients upward toward the driver's neck).

Despite these actual and potential negatives, NHTSA has modified its rule to allow the depowering of airbags. Ford Motor Company announced that most of its 1998 models include depowered airbags.

FMVSS 208 still needs to be upgraded and made more inclusive toward protecting children and shorter drivers. NHTSA needs to expand the crash test matrix to include 5th-percentile women drivers, and infants and small children on the front passenger seat. NHTSA needs to establish a minimum speed below which the airbags should not inflate. NHTSA needs to encourage airbag inflation pressures and expanding bag shapes that are proportional to the crash severity ("soft" and "medium" and "firm"). NHTSA needs to mandate or encourage adoption of seatbelt pre-tensioners, which automatically snug or tighten the lap and shoulder belts at the start of a crash. NHTSA needs to require frontal offest crashes, which is more realistic to actual accidents, rather than the car's entire front crashing into a flat-faced barrier.

TAILOR THE INFLATION PRESSURE TO THE SPECIFIC SITUATION: SEQUENTIAL AND MULTI-STAGE INFLATORS

It appears appropriate to *"re-invent"* an even better version of the 1973-through-1976 GM dual-pressure mode airbag system which had *both* a *"softer"* inflation and a *"firmer"* inflation, depending on the speed of the crash. The dual-pressure concept had merit back then, and the merits of the concept could be implemented again with the newer and superior technology that has been developed in the intervening years.

It is clearly feasible to develop an airbag system that automatically adjusts inflation rate and pressure proportional to the severity of the crash. The more severe the crash, the quicker the bag inflates and the firmer it gets. The ability to inflate the airbag proportional to the crash severity is similar to the two-stage capability of the General Motors dual-mode airbag system of the 1973-76 era. The current 1998 Lexus airbag inflator system, which uses a stored argon gas generator, appears to be close to having that capability.

Sensors are needed in the front seats and/or instrument panel to determine the weight of the occupant (or whether there's a child safety seat) on the seat and/or the *occupant's proximity to* the stored airbag. Sensors and stored algorithms should be used to determine the relative severity of the impact, and cause the airbag to inflate in proportion to that crash severity (soft, medium, firm), and relative to the weight of the occupant.

The inflation can be accomplished sequentially, such as by igniting an initial amount of sodium azide to begin filling the airbag. And then, about 10 to 15 milliseconds later, ignite the second amount of sodium azide. Thus, a more gradual build-up of inflation will take place... more like an "S" shaped curve, rather than an initial steep rise.

The inflation can be accomplished in multi levels, with multiple inflation pressures tailored to the severity of the crash. For example, a stored gas alone can provide a basic pressure, which can then be increased by also igniting sodium azide to boost the pressure with additional nitrogen gas. Also, multiple chambers of either stored gas or sodium azide (or other chemical propellant) could be selectively fired as needed to provide inflation pressures proportional to the situation of crash severity and occupant size.

CRASH SENSORS, THEIR LOCATION AND DEPLOYMENT THRESHOLD

Innovative crash sensors can lead to a slower-inflation rate airbag that is thus less explosive and less likely to cause injury. Present-day airbags require the sensing, actuation, and inflation to take place within about 30 to 50 millliseconds. The need for such rapid airbag deployment has led to various pyrotechnic gas-generating inflators that cause virtually an explosive inflation of the stored airbag, so the airbag can be fully inflated before the occupant moves significantly forward in the frontal collision.

The crash threshold for triggering a crash sensor should be related to the various velocities, accelerations, and decelerations that the vehicle experiences. The crash sensors and the supporting analytical electronics must detect and distinguish between crashes that require the airbag to deploy, versus low-speed incidents and non-crash jolts (hitting curbs, speed bumps, potholes) that should preclude the airbag from deploying.

The crash sensor triggering threshold has been from about 8 mph in some systems, to about 15 mph in others. The velocity is expressed in terms of the equivalent full-frontal crash of that same vehicle into a fixed barrier, thus "BEV" for Barrier Equivalent Velocity.

Most modern airbag systems include a computerized diagnostic module in which stored algorithms compare the incoming crash sensor signal characteristics with stored patterns. If the comparison shows that a valid crash is occurring, the airbag is caused to inflate.

If the sensing could take place even before the crash began to occur, that would allow more time for that sensing-to-actuation-deployment sequence to occur. That would enable a slower, safer rate for the stored airbag to become fully inflated.

Toyota had developed and tested such a pre-crash sensor system... back in 1970. The Toyota airbag system employed a radar sensor device and a small computer to sense and measure the distance between the car and the on-coming obstacle. The computerized decision to trigger the airbag allowing greater time to inflate the airbag... thus it could inflate with less explosive force. Toyota's car-into-barrier crash tests demonstrated the merits of such a pre-crash sensor.

It is important to locate and mount the crash sensors in the vehicle so they will respond to the vast range of frontal and front-angular crashes. The response time must be within 5-to-20 milliseconds, in order to allow enough time to complete the entire airbag inflation process before the occupant has moved too far forward into the airbag's primary deployment zone (typically the first five inches from the airbag cover, and the zone in which the "burst out" highest pressures occur).

Each vehicle has its own unique "crash signature" as to how the frontal structures will deform, buckle, and crush in various crash modes. The location of the forward crash sensors is typically near the front bumper or headlights, often mounted on a radiator cowl crossmember. The safing sensor, which must be activated simultaneously with a forward crash sensor, is typically mounted within the central cowl region (approximately adjacent to the driver's right knee).

If the locations of the forward sensors and safing sensor are not optimally selected, it can cause the inadvertent actuation of both sensors in such events as a low-speed impact into a parking lot curbing.

Analysis of one such incident showed the poor location of the right-hand forward sensor just above the front of the right-hand subframe member, and the safing sensor near the base of the right-hand windshield pillar and in-line with the same right-hand subframe member.

Thus, a very minor underbody contact between the curb and the subframe member was sufficient to trigger both the forward sensor and the safing sensor... and the airbag was fired in a situation in which it shouldn't have deployed at all. The short woman driver, wearing her seatbelt, was severely injured, including multiple major fractures of her jaw, and a shattered right wrist.

Crash sensors must be able to respond to impacts into flat walls, whether full frontal or offset involving only a portion of the vehicle's front structures. Crash sensors must be able to respond to car-to-car collisions, whether angular, offset, or full-frontal. Crash sensors must also be able to respond to vehicle impacts into a pole or tree, noting that such impacts could occur anywhere along the front of the vehicle... outboard near the headlights, possibly in-line with the front subframe members, or directly in the middle of the vehicle front.

Therefore, the precise location of the crash sensors, and how they are mounted to the vehicle, becomes important if the full array of potential collisions is to be taken into account. The fewer the sensors, the more difficult the challenge.

AIRBAG FOLDING PATTERNS AND MATERIALS

The airbag is typically folded into a very small package that enables it to be stored with the center of the steering wheel, and within the right-hand side of the instrument panel. In a frontal crash of sufficient severity to warrant deploying the stored airbag, a large volume of gas is instantaneously generated and routed to the stored, folded airbag. The airbag must then be unfolded as it rapidly inflates... all within about 20-to-40 milliseconds.

Since the unfolding, inflating airbag may contact the driver or passenger during the initial phase (the "punch-out" phase), it is imperative to avoid direct forces and uppercut forces to the neck, chin, or face.

Airbag folding patterns can also have an influence on the potential cause of injuries. Tests conducted by a major airbag system supplier appear to indicate that a "bias" folding pattern can help reduce the inflating airbag's interaction with the driver's neck. A more common "W-fold" pattern can increase the upward or uppercut forces under the driver's chin. A "star" folding pattern is preferable in that it appears to reduce neck shear, neck tension, and neck extension forces.

The airbag material itself can make a difference in the inflation pressure, the injury potential, and the ride-down venting. Nylon interwoven fabric, often with a thin neoprene inner-surface coating, has been common. Thinner weaves and other synthetic fibers have made airbags lighter and more easily inflatable.

AIRBAG TETHERS AND INTERNAL CHAMBERS

An airbag is basically a hollow fabric ball that gets quickly inflated by a burst of nitrogen gas... and it goes from folded to inflated in about 30 milliseconds. Most inflated shapes initially were like large rounded beachballs or basketballs. and the overall shape was determined by the sewn-together nylon fabric panels, and how it expanded outward under high internal pressure.

The use of internal tether straps, connecting the airbag module to the center portion of the fabric bag, enables a flatter pillow shape to occur, and the excursion distance toward the driver is also reduced. The flatter pillow shape can provide broader coverage in front of the driver, so the broader airbag would offer better protection in offset and angular crashes. And the greater distance from the driver means less injury potential. NHTSA tests have shown that tethered airbags have an excursion distance of only 12-to-15 inches from the steering wheel, while untethered airbags have a more potentially-harmful excursion distance of 17-to-20 inches.

While many automakers opted for internal tether straps to better shape and reduce the excursion of driver airbags, other automakers did not initially use tethers. Tethers for driver airbags are now common, but only a few passenger airbags utilize them... even though the merits of tethers would still apply to better shape the larger passenger-side inflated airbag and reduce its excursion distance toward the passenger.

The manner of inflating the airbag can be improved by constructing the airbag with multiple chambers. One approach is to initially fill an inner chamber and allow the nitrogen gas to then continue swirling into the outer chamber, thereby creating a "softer" outer bag and a "firmer" inner bag.

The reduction and control of the inflation gas, whether from the combustion of sodium azide or from stored argon gas, can be accomplished with internal gas diffusers and nozzles that direct the gas into the airbag in a circumferential manner or in an up-and-down or lateral manner. Thus, the burst of gas is directed in a safer manner, rather than directly toward the occupant.

AIRBAG MODULE COVERS

The cover over the driver's stored airbag module must serve multiple purposes, as a decorative yet resilient cover in the center of the steering wheel, yet allow the stowed airbag behind it to instantaneously inflate while moving the cover out of the way.

Thin cross-section lines, or partimg lines, allow the inflating airbag to "burst through" the cover in a pre-determined manner. Most are in an "H" shaped pattern, with two vertical parting lines and one horizontal parting line.

However, others are top-hinged and, with a cover that may be about 8 inches from top to bottom, allows a forceful upswing of the entire cover as the airbag inflates behind it. In a recent accident case example, involving a 1995 model luxury sedan, a 4'10" shorter woman driver received a severe uppercut punch beneath her jaw when the leather-covered cover pivoted forcefully upward.

DRIVER AIRBAG RECESS AND RETRACTION MECHANISMS

In respose to the airbag inflating outward toward the driver, there are various ways to help conteract the inflating airbag's initial burst-out forces. The airbag module could be mounted deeper within the hub of the steering wheel. The airbag module could simultaneously retract deeper into the steering wheel hub as the airbag inflates outward toward the driver.

Initially recessing the airbag module an inch or so deeper into the center of the steering wheel can have a notable effect of reducing the airbag-inflation "burst-out" injury potential to the driver.

Similarly, allowing the driver airbag module, as it inflates, to simultaneously move deeper or retract into the steering wheel, can also have a similar effect on reducing "burst-out" inflation injuries. This can be mechanically accomplished by a movable or deformable linkage or mounting bracket for the airbag module.

TOP-MOUNT PASSENGER AIRBAG WITH INITIAL VERTICAL DEPLOYMENT

The passenger-side airbag has been stored in many different locations: on the front face or angled face or top face of the instrument panel. Various crash tests, including those done by Minicars and by Honda in the early-1980's, indicated that top-mounted airbags that initially inflated upward, and then continued rearward toward the occupant, would reduce the injury potential to any children in the front seat area, including those who were out-of-position.

Thus, it is apparently safer to utilize a top-mount, vertical-deployment airbag for the passenger, since the airbag's initial burst-out forces are first directed upward toward and into the sloped windshield glass, and then the inflating airbag continues rearward with reduced force toward the seated passenger. The less desirable alternative is a front-mounted airbag that inflates directly horizontally rearward directly toward the seated occupant, who could be a small-stature adult or child, and who may have moved forward during pre-crash braking.

USE OF "ON-OFF" SWITCHES

Some automakers include or offer an available "on-off" switch to allow parents to turn off the potential activation of a passenger-side airbag. That would introduce the danger of their failure to turn the airbag back on, to protect larger children, teenager, and adult passengers, especially in the more severe frontal impacts when the combination of seatbelts and airbags is most critically needed.

A critical requirement for any airbag "on-off" switch would be to include a *lighted visible alert* on the instrument panel, with an amber or red light and wording and symbology to clearly indicate that either or both the driver's and passenger's airbags have been turned off. A green light would indicate that the system is ready for actuation when appropriate. It's also possible to design the airbag system so that it automatically re-sets to a ready mode each time the car is started.

SIDE AIRBAGS FOR TORSO AND HEAD PROTECTION

The latest airbag application is for side-impact protection. Volvo began utilizing side airbags in 1994, in a joint development program with Autoliv. The stored airbag was located within the outboard portion of the driver's seat and the right-front passenger's seat. Thus, the Volvo airbag protected the adjacent occupant's torso, and helped keep their head from being impacted by inward intrusion or lateral displacement.

The newest Volvo airbag system is the *"Inflatable Curtain"*, which is stored along the roof siderail, and inflates downward and longitudenally along the upper half of the side windows, and offers head protection to front and rear seat occupants in side impacts and rollovers.

BMW has recently shown their version of airbags for side-impact protection, including the mounting of one airbag within the upper door structure and another tubular-shaped airbag that inflates to offer protection from the windshield pillar to the mid-body pillar. Thus, this second or upper airbag more directly protects the head of the adjacent occupant.

Various side-impact airbags from Volvo, BMW, Mercedes, and Ford show alternatives for mounting the airbag... within the outboard portion of the front seat, or within the door just below the window level, or along the roof siderail (essentailly between the windshield pillar and the mid-body pillar).

The BMW design, first implemented in some of its 1997 models, is especially meritorious in having an upper-level tubular-shaped airbag that protects the head of the driver and right-front passenger. The front anchorage is at the windshield pillar, and the rear anchorage is at the top of the B-pillar. Once inflated, this head-protecting side airbag commendably stays inflated for a prolonged interval to help continue its effectiveness throughout what could be a more complex accident scenario, including a vehicle rollover.

It is apparent from crash testing demonstrations and from actual accidents involving Volvo, BMW, and other vehicles equipped with side airbags, that reasonable levels of injury reduction can be attained with side impact airbags. The technology is now available to have side impact airbags inflate within 20-to-30 milliseconds of the onset of a side impact to the subject vehicle. There are various storage cavities for the airbags that can be available by feasible redesign of the the seat, the door, or the roofrail. The crash sensors and gas generators have response and actuation times to ensure airbag inflation in sufficient time (e.g., within about 10-to-20 milliseconds).

Side impact airbags for front seat (and also rear seat) occupants are feasible in various designs.... as inflatable protective cushions for the pelvic, torso, head, and neck. The seat belt system will likely need to be integrated into newly-designed and strengthened front seats, rather than having the shoulder belt attached to the mid-body B-pillar, so as to avoid interfering with the inflation of side-impact airbags.

CONCLUSION

NHTSA's mission is to maximize motor vehicle safety, and issues Federal Motor Vehicle Safety Standards (FMVSS) to help encourage implementation of safety technology. While some automakers attempt to comply with the minimum FMVSS requirements, other automakers try to significantly exceed those minimum requirements. Some automakerts try to be at the forefront in developing safer vehicle technologies, including better airbag systems that significantly exceed the minimum requirements of the Federal Motor Vehicle Safety Standards.

Airbags are marvelous safety devices that will continue to save many lives, of adults and children, in collision accidents. The serious concerns about some airbag systems causing severe to fatal injuries to children and to shorter drivers must be expeditiously addressed and corrected.

So-called "smarter" airbags systems, many with features discussed in this paper, could and should have been implemented many years ago. They should now receive the highest attention by the auto manufacturers, the airbag system manufacturers, and the National Highway Traffic Safety Administration.

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