

A Treatise on Crash Sensing for Automotive Air Bag Systems

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Abstract—During the decade of late 1980s–1990s, air bags became standard equipment for all new passenger vehicles manufactured and marketed in the United States. Despite the effectiveness of air bags evidenced by accident statistics, a number of inadvertent fatalities and injuries have been caused by air bag deployment. This misfortune has prompted the government and the industry to pursue so-called “smart air bags” for upcoming years. An essential focus of potential enhancements to air bag systems centers around crash sensing technologies. This paper provides a basic yet thorough discussion of underlying technical challenges and design approaches for the subject matter. The paper starts with an introduction to the basic functioning principles of crash sensors. Descriptions are given for specific design examples, including mechanical and electronic sensors. Mechanical sensors are analyzed to reveal their functioning characteristics. Discussions of design approaches for electronic sensor are elaborated with analysis of sensing algorithms. Subsequently, the shortcomings of current systems are cited to establish the needs and the requirements for advanced systems. Definitions and compositions of smart air bags are then summarized. Included in the discussions are the subjects of occupant sensing and integrated sensing systems, which are critical to the availability of advanced air bags. Also presented is a perspective on system design of occupant restraints that relates to the concept of energy management in vehicular safety systems. The implementation of air bags and related occupant restraints requires extensive knowledge from various engineering disciplines, in particular mechanical, chemical, electrical, and increasingly electronic expertise. It is a subject presenting truly challenging tasks in both analytical and experimental phases of product developments. Over the last decade of developments, it has become obvious that: 1) the market is evolving toward a greater usage of electronic contents, and 2) the demand of advanced functions is stimulating the integration of various sensing technologies. Research and development activities in related areas are likely to continue for years ahead.

Index Terms—Air bag, automotive safety, crash sensing, occupant restraints.

I. BACKGROUND

THE AIR BAG industry experienced tremendous growth in the United States during the decade from late 1980s to late 1990s. Several factors contributed to the standardization of air bags, including:

- a) government regulation;
- b) public awareness of vehicle safety needs;
- c) readiness and affordability of technologies;
- d) mass production and cost reduction.

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The journey leading to the acceptance and implementation of air bags as a common occupant restraint device has not been smooth, and in fact turbulent at times, with issues on technical, economical, political, and societal aspects widely debated over the years [1].

A. Air Bag History

The idea of utilizing an air cushion to soften the impact on occupant was conceived in the 1950s. The initial availability of technologies was established in the 1970s. Nevertheless, the penetration of air bags as a popular consumer product did not occur until the 1990s. Certain milestones of air bag developments in the United States are highlighted in Table I.

B. Field Experience of Air Bags and Recent Developments

In recent years, given the increasing number of vehicles equipped with air bags on the road, data have been collected to evaluate the effectiveness of the device. Accident statistics showed that the benefits of reducing fatalities and mitigating injuries are being realized. However, a number of incidents caused by air bags, which resulted in fatalities and injuries, especially to children, have raised public concerns in recent years. A recent update [3] shows that as of November 1999, while more than 4800 lives have been saved, 86 children and 62 adults have been killed due to the deployment of air bags.

With an increasing number of incidents in recent years that involve occupant injuries or fatalities caused by air bag deployment, there is an urgent need to improve the effectiveness of occupant restraints. In particular, concern for the out-of-position occupant, a long-standing design issue, is now the focus of attention. An “out-of-position” situation arises when an occupant, adult or child, is situated too close to the air bag module in the deployment process.

Recently, the automobile industry has taken steps to improve the performance of air bags. Corrective or temporary measures being evaluated or implemented include the option to turn off the passenger-side front air bags or to de-power the air bags, i.e., reducing the energy release level. Also being pursued is the technology and implementation of smart air bags [4]. More discussions on the subject of smart air bags are covered in Section IV.

II. PROBLEM DESCRIPTION OF CRASH DETECTION

There are four essential components in an air bag system: sensor, inflator, bag, and vehicle interior. Sensors are the brain and nerve of occupant restraint systems; their role is to detect the occurrence and to judge the severity of an impact. If a situation

TABLE I
MILESTONES IN U.S. AIR BAG DEVELOPMENTS

Year	Events
1953	The first U. S. patent on air bag systems was issued to J. W. Hetrick on August 18, 1953 [2].
1973	General Motors pledged to voluntarily build one million airbag-equipped cars in the 1974 model year. Actual production was limited to 10,000 1974-75 models.
1970s-1983	A continual struggle with air bag standard persisted for many years. The standard was issued, rejected, reissued, and revoked with the involvement of government, auto industry, and other agencies. A legal case eventually went all the way to the Supreme Court, and was finally sent back to the Department of Transportation (DOT).
1984	The air bag standard was reinstated by DOT and FMVSS 208 passive restraint rule was adopted. NHTSA agreed that automobile makers might offer a choice of restraints. Air bags or automatic seat belts would be phased in over a 4-year period beginning with 1987 model year.
1991	DOT extended the rule of air bag installation to light trucks and vans over a 4-year period, beginning with 1995 models. Congress passed a bill requiring air bags in both front-seat positions in all passenger cars by the 1995 model year and all light-duty trucks by the 1997 model year.

is appropriate for air bag deployment, the sensing system sends an electrical signal or trigger a mechanical mechanism to start the reaction in the inflator. The inflator generates gases, which then flow out to fill the bag. The inflated bag provides a cushion to absorb the kinetic energy of the occupant. The vehicle interior, such as the steering wheel and the instrument panel, is engineered to accommodate the installation of the air bags. Since the emphasis of this paper is on crash sensing, discussions here are mostly limited to sensors. An extensive body of literature exists for other components and their design issues, but these topics are not covered in this paper.

A. Functioning Sequence of an Air Bag System

Fig. 1 illustrates the following sequence of an air bag deployment during a collision.

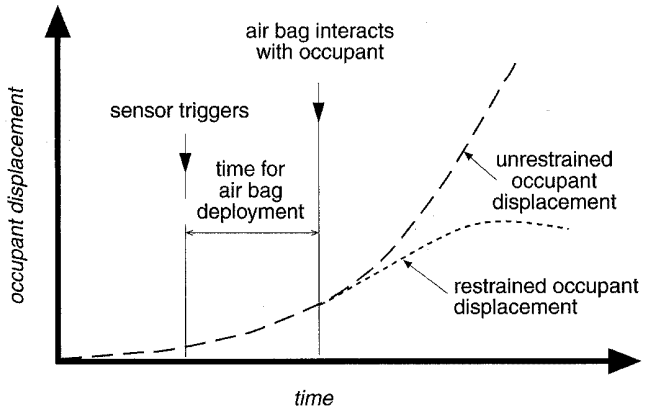


Fig. 1. Functioning sequence of an air bag system.

- From the onset of a collision, crash sensors are triggered within 10–50 ms. The actual timing depends on several factors, which will be discussed in Section III.
- After receiving a firing signal from the sensors, the inflator fills a bag within 30–60 ms. Some inflators generate gases by a chemical reaction of pyrotechnic materials while others release from containers of compressed gases. A hybrid type with a mixing of chemical reaction and compressed gases is also available.
- One or more orifices on the backside of the air bag allow gases to flow out of the bag as it expands. As the occupant comes into contact with the inflated bag, thus pressurizing the bag further, the bag becomes deflated within 75–150 ms.

The sensing-inflation-cushion-deflation process of air bag deployment takes only a fraction of a second. To achieve the maximum benefits of a restraint system, the deployment sequence must work properly. The sensing system must trigger in time to initiate the bag deployment so that a sufficiently inflated bag is in place to cushion the occupant motion. If an occupant has excessive forward excursion and is very close to the air bag module when the deployment occurs, the unfolding bag can exert considerable forces to inflict injuries to the occupant.

B. Timing of Sensor Triggering

Since the whole deployment event is initiated by the triggering of the sensor(s), crash sensor design plays a critical role in realizing the effectiveness of occupant restraint systems. One basic rule of thumb for determining sensor-triggering time is the so-called “125 mm minus 30 ms” criterion. This rule simply means that the required or latest sensor triggering time is determined by subtracting 30 ms from the elapsed time when the occupant has moved forward by a distance of 125 mm from the onset of a crash. This criterion can be reasoned by the following assumptions.

- The estimated distance between a fully inflated bag and the chest or head of the occupant in his original seating position at the onset of the crash is 125 mm.

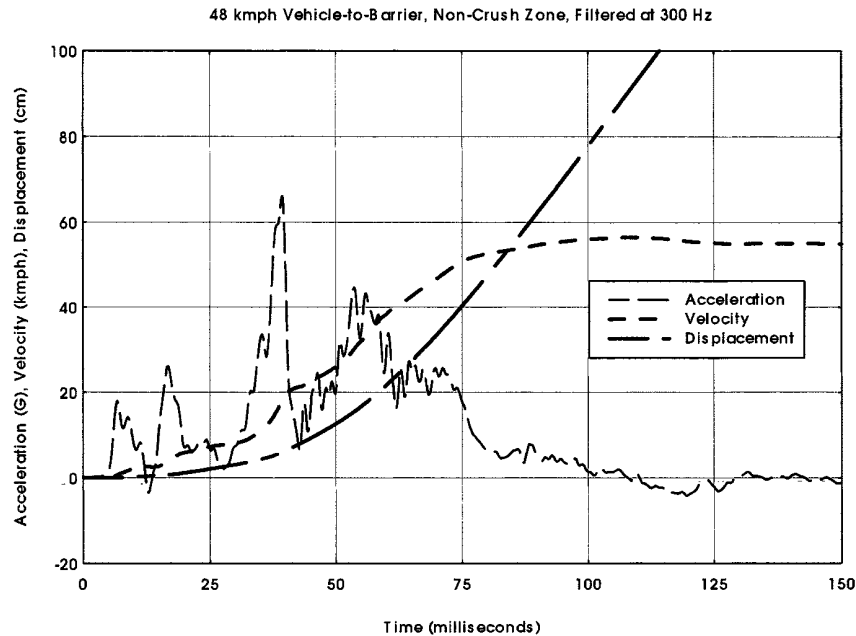


Fig. 2. Crash data of a 38-km/h vehicle-to-barrier collision.

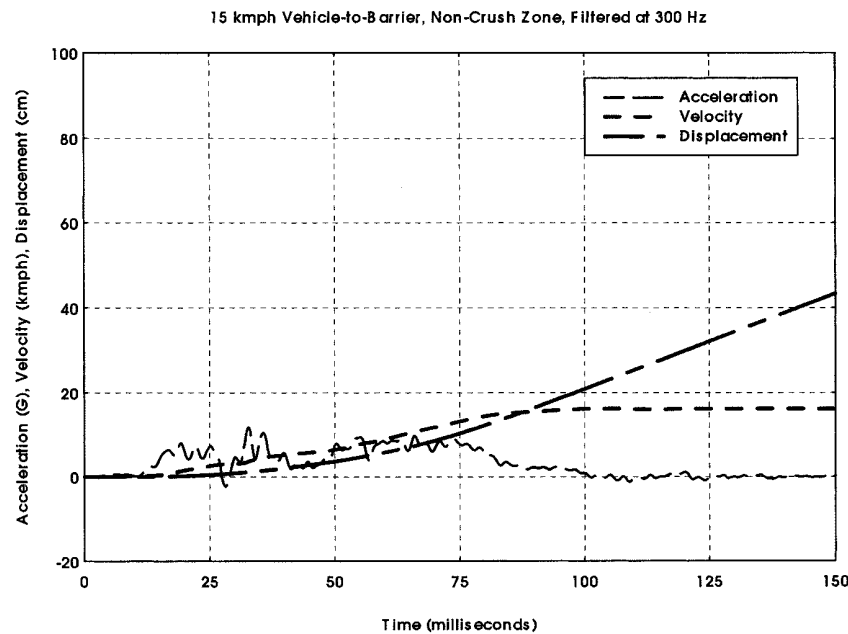


Fig. 3. Crash data of a 15-km/h vehicle-to-barrier collision.

b) Once the inflator receives the firing signal, the time needed for the bag to become fully inflated is 30 ms.

Figs. 2 and 3 show acceleration signals measured at a passenger compartment location of the same vehicle in two different crashes. Also shown in the plots are the first and second integrals of the acceleration pulses, representing rough estimates of the speed and displacement of an unrestrained occupant in the crash. By using the “125 mm minus 30 ms” criterion explained above, one can derive that the proper sensor triggering time is about 18 ms for the 48-km/h crash and 50 ms for the 15-km/h crash.

The “125 mm minus 30 ms” criterion is an oversimplified approach because it does not take into account the variation of many factors. Occupants of different sizes seated at various positions are not at the same distance from the steering wheel or the dashboard. Inflators with different performance characteristics require different inflation times. The criterion is only adequate for a first-order approximation of determining sensor-triggering time.

In reality, the determination of proper sensor-triggering times involves a far greater complicated process than the aforementioned procedure. For example, the available space for occupant

movement and restraining loads on an occupant should be used as performance measures [5]. Variations in the vehicle interior, such as steering wheel deformation and steering column rotation, also play roles in the determination of design specifications.

In the design process, a series of crash data is compiled to constitute a crash library. A sensing system must satisfy the performance requirements for all crashes in the library. For every crash that demands the deployment of air bags, one specific sensor triggering time is designated. For every crash where no deployment is needed, the sensing system must avoid faulty triggering.

Table II offers a set of appropriate sensor triggering times for different types of frontal collisions, involving typical passenger cars. The numbers are estimated by examining real-world crash data, and they vary with vehicle models under different crash conditions.

C. Crash Sensing Characteristics

The design of an effective crash sensing system is technically challenging. The task of crash sensing possesses the following characteristics.

a) *Predictive:*

Since an air bag requires a finite time span to inflate, the sensing system must be predictive. Sensors, individually or as a whole, must make a judgment about crash severity at the early stage of a collision.

b) *Discriminative:*

It is essential that a sensing system be able to reliably differentiate the circumstances of deployment and nondeployment. Unnecessary deployments become a nuisance to the users and present potential hazards.

c) *Real-time:*

Crash sensing is a real-time application, which means that sensors must react immediately upon the received signal in a limited window.

The three characteristics listed above are interconnected. If a sensing system is extremely sensitive there is a higher probability of detecting crashes earlier or to make better predictions, but it may also make the system less discriminative. Because sensor-triggering time occurs on a real-time basis and cannot be reversed once a triggering signal is released, the sensing system must be discriminative. The key to the successful design of a sensing system lies in achieving these objectives altogether in a robust manner.

III. ANALYSIS OF CURRENT CRASH SENSORS

Several concepts have been implemented in crash sensors for air bags. Each sensing concept is based on the measurement of a physical variable or the interpretation of a measured signal. Candidates among such variables or signals include speed change or ΔV , damage or crush, and acceleration measured at various locations of a vehicle. Regardless of the selected approach for crash sensing, potential solutions must satisfy two criteria:

- 1) the selected measure correlates well with crash severity;
- 2) the selected measure can reflect crash severity in advance and, thus, establish a predictive indicator.

TABLE II
SENSOR TRIGGERING TIME FROM THE ONSET OF A COLLISION, IN VARIOUS TYPES OF CRASHES FOR PASSENGER CARS

Types of Crashes	Sensor Triggering Time (millisecond)
Head-on collisions below 14 kmph, Rough road, Minor animal-impact, Braking	No Triggering
48-64 kmph Vehicle to rigid barrier	10-20
48-64 kmph Vehicle to angular rigid barrier	20-30
24-32 kmph Vehicle to rigid barrier	30-50
24-32 kmph Vehicle to pole	50-70
48-64 mph (closing speed) Vehicle-to-vehicle head-on collision	30-50

Among the crash sensing methods suggested over the years, most notably are approaches that rely on the detection of speed change [6] and acceleration-based signal processing [7]–[9] for frontal air bag systems. For side impact air bags, mechanical crush switch [10], [11], and pressure or acceleration sensing schemes [12] have been implemented.

In terms of the physical construction of actual sensing devices used in air bag systems, crash sensors can be classified into two basic categories: (a) mechanical, and (b) electronic. Many sensors in various configurations fall into the first category, despite their distinct appearance and functional principles. These sensors contain a sensing mass, which moves when a vehicle is involved in a collision. If the sensing mass travels beyond a certain limit, it results in a mechanism release or a circuit closure, thus triggering the crash sensor. Sensors in the second category contain a transducer that generates a crash signal, and electronic circuitry that processes the generated signal. The functioning principles of these devices are analyzed in further details in the following sections.

A. Mechanical Crash Sensor

There are several types of mechanical crash sensors; some rely on electrical or magnetic phenomena to operate while others are purely based on mechanical mechanism. The various types are loosely grouped under the “mechanical” category. The term, “mechanical”, refers to a common characteristic of these sensors, in which a crash is indicated by monitoring the motion of a sensing mass.

1) *Crash Sensor With Damping:* One type of widely used sensors for air bag systems in the late 1980s and early 1990s is the so-called ball-in-tube sensor [13], depicted in Fig. 4. The operation of this sensor depends on the motion of a ball contained in a tube. A magnet situated at one end of the sensor attracts the ball toward that end of the tube. Under regular driving or braking conditions or even in minor collisions, the force of magnetic attraction prevents the ball from moving. When a collision occurs, the ball breaks away from its resting position. If the impact is sufficiently strong and lasts long enough for the ball to move to

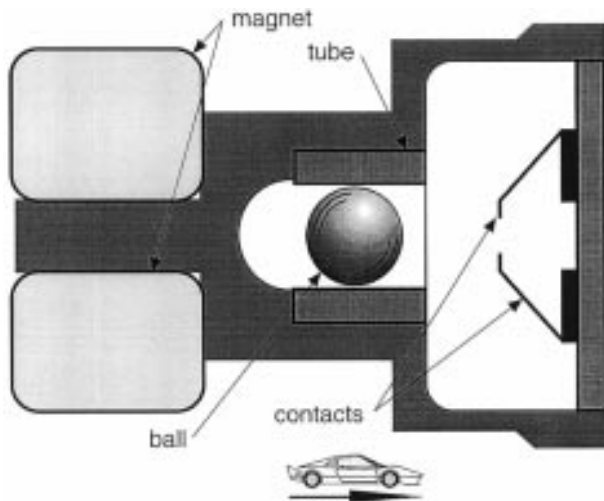


Fig. 4. Ball-in-tube sensor.

the contacts at the opposite end of the sensor, the gold-plated ball bridges the two contacts and closes an electrical circuit.

When the ball moves along the tube, the air inside the sensor flows through the clearance between the ball and the tube. The airflow generates an aerodynamic drag force that dampens the ball's motion. The magnitude of the damping force depends primarily on the speed of the ball and the tightness of the clearance. Other factors, such as the amount of air and the pressure and temperature inside the sensor, also affect the damping phenomenon.

Physical configurations may vary for sensors utilizing the same principle described above. For example, a purely mechanical unit was built by replacing electrical contacts with a pin-releasing mechanism and the magnet by a bias spring [14]. The key feature in this type of sensors is the presence of a damping effect, but the implementation of damping is not limited to a drag force by air. Another sensor example utilizes electromagnetic damping to create similar effects [15], [16].

2) *Spring-Mass Sensor*: Another commonly used crash sensor is the so-called Rolamite sensor [17], depicted in Fig. 5. The motion of a roller dictates the function of this sensor. Held in place by a metallic band-spring, the cylindrical roller rests against the stop post during a vehicle's normal operation. In the event of a substantial collision, the roller overcomes the spring force and rotates forward. If the impact is severe enough, a moving contact on the metallic band touches a fixed contact and closes a circuit.

Unlike the ball-in-tube sensor, there is no damping force involved in the roller motion of a Rolamite sensor. The sensitivity of a Rolamite sensor is controlled by two parameters: (a) the distance to trigger, and (b) the magnitude of the spring force. The spring force, sometimes called the biasing force or the bias, is usually given in a ratio of the bias force to the weight of the sensing mass.

The defining characteristic of the Rolamite sensor is the combination of a sensing mass and a bias spring. The configuration of components in spring-mass sensors can be quite diverse. For example, the sensing mass can be arranged to slide within the sensor [18] or to rotate around a pivoted axis [19].

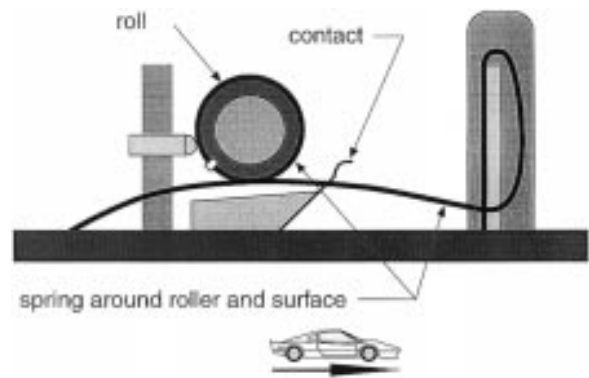


Fig. 5. Rolamite sensor.

3) *Performance Characteristics of Mechanical Crash Sensors*: The sensitivity of mechanical sensors depend on design parameters, such as bias ratio and damping phenomena cited in the examples above. In production, sensors of different sensitivity levels are created with the proper selection of associated parameters. For a particular vehicle platform, one or more sensors with different design specifications are placed on appropriate locations to constitute a complete sensing system.

A crash pulse must last long enough for the sensing mass to move to the trigger position. When acceleration is integrated over the pulse duration, it yields a speed change or ΔV experienced at the sensor location. The minimum ΔV required to trigger a sensor is sometimes referred to as the marginal ΔV , which is a performance measure. With a mathematical analysis of the sensing mass motion, it can be concluded that most mechanical sensors function as ΔV -dependent devices.

From a design perspective, the bias existent in all mechanical sensors is mandatory. It is necessary to restrain the motion of the sensing mass in regular driving conditions or minor impacts by imposing a biasing force. The bias will also ensure that the sensing mass returns to the resting position after excursions. The bias creates an increase in marginal ΔV so that in a long-duration situation such as a braking maneuver the marginal ΔV will be high enough to prevent sensor triggering.

B. Electronic Sensors

In the late 1980s and early 1990s, most crash sensors used by U.S. automobile manufacturers were mechanical, electromechanical, or magnetomechanical types explained in Section III. Beginning in the early 1990s, electronic sensors began to gain market shares in the U.S. market. An electronic sensor contains one or more accelerometer and accompanying circuitry to process the acceleration signals. With the implementation of sophisticated algorithms in electronic circuits, these sensors potentially can detect and differentiate crashes more "intelligently" than traditional mechanical sensors.

One of the primary driving forces behind the adoption of electronic sensors is that they are excellent candidates for the concept of single-point sensing. Single-point sensing concept implies using only one sensor unit, typically installed at a location in the passenger compartment, which by itself constitutes the whole sensing system. If the concept is successfully implemented, the wiring to multiple locations can be eliminated

and the vulnerability of multiple components can be mitigated. The overall system cost can also be potentially reduced.

1) *Functions and Components of Electronic Crash Sensors:* Fig. 6 is a diagram depicting the “blocks” that constitute a typical electronic sensor. One essential component in the sensor is an accelerometer or transducer that measures the crash signal experienced at the installed location. The signal first passes through a filtering and signal-conditioning unit. The filtered signal is next fed into a main processing unit, which performs the embedded sensing algorithms. Logically connected to the main processing unit is a comparator block where parameters are stored in memory or evaluation circuits are constructed. With signal processing techniques, information is extracted from the transducer signal. The calculated data is then compared to the parameters stored in the comparator blocks before a decision is made. At the output stage, if the embedded algorithms indicate that a triggering action is warranted, the main processing unit sends a triggering signal to the firing circuit to deploy the restraint system

The implementation of electronic sensors for air bags are summarized below:

- 1) acceleration signals, generated by accelerometers, provide the basis of crash recognition;
- 2) signal processing is used to identify the unique properties of crash signals;
- 3) procedures of signal processing or sensing algorithms are implemented in electronic circuits to correlate signal properties with crash conditions;
- 4) multiple algorithms can be integrated, in parallel or in series, to enhance the reliability of crash recognition;
- 5) information received from other devices on a vehicle, such as seat belts or occupant sensors, can be combined into the electronic sensor unit to optimize the performance of restraint systems.

Although the configurations of electronic crash sensors vary among manufacturers, a common list of their functions and components can be established. Hartl, *et al.* [9] provided a comprehensive list. Two essential components are mentioned here.

In a majority of electronic sensors designed for frontal air bags, an acceleration pulse is the signal source used for crash detection. The signal is generated by an accelerometer, which can be piezoelectrical [20] or micromachined [21]–[23]. Bergfried *et al.* [24] indicated that a range of ± 35 g and a bandwidth up to 300 Hz are appropriate for accelerometer applications in crash sensors. Kelly [25] stated that a range of ± 25 g to ± 50 g was acceptable. When choosing accelerometers, it is necessary to consider size, cost, sensitivity, offset, output noise and EMI effects. Built-in diagnostic and self-testing functions may also be required.

A mechanical arming sensor is often incorporated in single-point sensing systems with electronic crash sensors. Its function is to reduce the potential for inadvertent deployment in the presence of certain faulty conditions or electromagnetic interference (EMI) effects [25]. The calibration of an arming sensor is selected to ensure that no actuation results from normal driving conditions. Most electronic sensors adopts mechanical arming sensors of a spring-mass type, however arming sensors based on logic-level electronics are being developed [26].

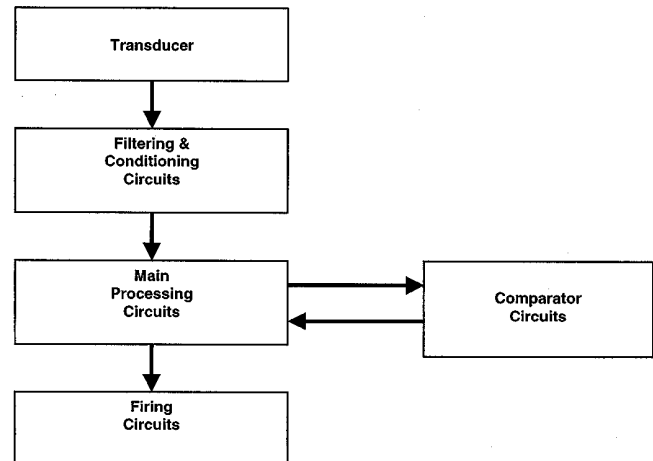


Fig. 6. Conceptual blocks of an electronic sensor.

2) *Sensing Algorithms in Electronic Sensors:* The core element of an electronic sensor is the embedded sensing algorithms, within which the decision to deploy air bags is made. Criteria used in the considerations for sensing algorithms include performance, robustness, calibratability, flexibility, and complexity [25].

Given below are a number of illustrative algorithms selected to explain various approaches of implementing sensing schemes. The examples included here do not represent a complete set of all possible algorithms. In fact, some algorithms in the list may have become outdated as newer ones are developed. The examples are chosen merely to show the diversity of approaches and techniques. A comparison of these algorithms and their main features is summarized in Table III. The logistics and reasoning of these algorithms are briefly outlined in the following paragraphs.

- 1) Diller suggested using energy levels in a crash as sensing criteria. The estimates of energy levels involved calculation of absolute values and differentials of acceleration [27], [28].
- 2) Allen proposed the use of power rate, a second derivative of kinetic energy, as the measure. The method determined crash intensity by combining measures of acceleration, jerk, and velocity [29].
- 3) Gioutsos asserted that jerk could be used as a basis for crash severity prediction. The method provided a time-invariant approach by identifying jerk values in the waveforms of acceleration pulses [30].
- 4) Watanabe and Umezawa suggested using predictions of occupant displacement to establish an optimal timing to trigger an air bag. The method included Kalman filtering of crash data and calculation of jerk, acceleration, velocity, and displacement [31]–[33].
- 5) Mattes *et al.* proposed the use of adjustable velocity thresholds. The threshold is varied according to accident situation and vehicle parameters [34].
- 6) Diller suggested a summation of multiple evaluation variables with selected weighting. The evaluation variables included velocity, jerk, and displacement values [35].

TABLE III
HIGHLIGHTS AND COMPARISONS OF A SELECTED LIST OF CRASH
SENSING ALGORITHMS

Author or Inventor	Main Theme or Features	Approach
Diller et al	Total and Partial Energies	Energy in Time Domain
Allen	Power Rate	Energy + Jerk + Acceleration + ΔV
Gioutsos	Waveform Recognition	Jerk
Watanabe & Umezawa	Optimal Timing	Predicted Displacement + Acceleration + Jerk + Energy
Mattes et al	Adjustable Velocity Threshold	ΔV
Diller	Summation of Expert Circuits	ΔV + Jerk + Displacement
Eigler & Weber	Multiple Evaluation Circuits + Time Window	Acceleration Recognition + Velocity + Displacement
Tohbaru, Blackburn, Blackburn & Gentry	Acceleration Power in a Frequency Range	ΔV + Energy in Frequency Domain
Cashler & Kelly	Occupant Displacement + Crash Severity	Jerk + Acceleration + ΔV + Displacement
McIver et al	Crash Velocity + Crash Metrics	ΔV + Acceleration + Shape Function
Sada & Moriyama	Adjustable Velocity based on Physical Quantities	Jerk + Acceleration + ΔV + Displacement
Kosiak	Crash Sensing using Anticipatory Sensor Inputs	Acceleration Scaling with Anticipatory Sensors

- 7) Eigler and Weber adapted multiple evaluation circuits to differentiate accidents types. The use of time window allowed the determination of optimal triggering time [36].
 - 8) Several alternative algorithms were adopted to calculate energy levels of a crash in the frequency domain, such as Tohbaru [37], and Blackburn *et al.* [38], [39].
 - 9) Cashler and Kelly proposed a two-step deployment control. A "time to wait" step determined the deployment timing and a "severity" step evaluated crash severity [40].
 - 10) McIvers *et al.* suggested the use of multiple crash metrics. The metrics included the values of acceleration, acceleration squared, sum of acceleration over a time period, and the shape of velocity curve [41].
 - 11) Sada and Moriyama proposed using adjustable velocity thresholds. The adjustment of threshold was based on physical quantities involving jerk, acceleration, velocity, and displacement [42].
 - 12) Kosiak suggested that anticipatory sensors mounted at the front of a vehicle could help prepare or arm the crash sensors [43].
- 3) *Design Methodologies of Crash Sensing Algorithms:* In the previous section, a number of sensing algorithms were outlined to demonstrate the diversity of methods that have been proposed for crash detection. A comparison of algorithm approaches is shown in Table III. These algorithms involve the use of the following common variables: speed change, acceleration, jerk, energy, and displacement. They are further discussed below.
- 1) *Speed change:*
The change in speed, or ΔV , is obtained by the integration of the acceleration signal. This variable is often used in conjunction with other variables and is present in almost all algorithms. Although appearing in different calculation schemes, ΔV remains an essential element of crash detection.
 - 2) *Acceleration:*
Raw output from the accelerometer is usually filtered before it is used for calculation. The acceleration magnitude is often compared to a threshold value before a crash condition is recognized. Most algorithms do not utilize the acceleration value directly but in a manipulated manner.
 - 3) *Jerk:*
The jerk variable is obtained by calculating the derivative of an acceleration sequence. A filter is usually involved before acceleration values are used in the differentiation calculation, since jerk values are subject to wild fluctuations if direct values are used. In another form of implementation, it can be reflected in the frequency domain, where a high level of power spectrum density in the high-frequency range also represents acceleration fluctuations and thus implies high values of jerks.
 - 4) *Energy:*
The energy variables correlate well with the severity of a collision. The physical meaning of an energy change during a collision can be easily comprehended, but the suggested calculation methods for estimating energy levels vary significantly among different algorithms. The energy level can be calculated in the time domain or the frequency domain.
 - 5) *Displacement:*
The direct measurement of occupant displacement is not a reliable index of crash severity. However, in several algorithms mentioned above, the predicted occupant displacement derived from the acceleration signal is proposed as a predictor to determine optimal timing. The robustness of these algorithms depends on the accuracy achievable in estimating the occupant displacement.
- Realizing the common variables used in sensing algorithms, one can construct a potential algorithm by selecting a few of these variables from the list above. The understanding of physical meanings behind these variables is important because it helps the validation process. However, figuring out the calculation steps for any of the variables is not trivial. The verification of algorithms involves a considerable effort to tune or refine the selection of variables and their processing steps.

The development of a sensing algorithm for crash sensing typically proceeds in the following steps.

- 1) Select a set of candidate variables, which represent physical connections to crash severity, and choose calculation schemes for these variables. For example, one's candidates may be energy and jerk. Define the methods to calculate these two values.
- 2) Determine the proper sensor triggering time for each crash in the crash library with techniques explained in Section II. Include in the library crashes where no sensor triggering are allowed.
- 3) Process crash data for selected variables in each crash up to the triggering time.
- 4) Analyze the calculated data from (c) to identify a set of threshold values for the candidate variables, which triggers in time for deployment cases and avoids triggering in nondeployment situations.
- 5) If the identified threshold values meet requirements in all crashes, the algorithm is successfully constructed.
- 6) If no appropriate threshold values can be identified, the algorithm is incomplete. Either the calculation steps need to be revised or the variables set need to be enhanced. Make adjustments and then repeat processes 1) through 4).
- 7) If new crash data becomes available, apply the algorithms and see if the sensor triggers in time.

C. Sensor Placement Strategies and Design Issues

With respect to the implementation of a sensing system on a vehicle, an equally critical problem is where to place the sensors and how these sensors work as a system. The first generation of sensing systems introduced in the last decade mostly employ a multiple-location or distributed system. Recently, an increasing number of platforms are adapting the concept of single-point sensing, where a single sensor typically in the passenger compartment represents the whole sensing system.

In addition to the number of sensors, there are other considerations for sensor placement. For example, the sensor location should experience minimum vibrations in normal or rough-road driving conditions. Obviously, the installation of sensors should not interfere or affect the operation or maintenance of other components. For crush-zone locations, the mounting bracket of the sensors must be attached to a sturdy structure. Front-end sensor locations ideally are chosen so that they are reactive to various types of crashes, such as offset, angle or pole impacts. Sensors in the passenger compartment, although away from the crush zone, must be mounted on a frame location to effectively receive the impulse to the frame of the vehicle for the sensor to function properly.

1) *Distributed Sensing*: To constitute a reliable and complete sensing system, conventional mechanical crash sensors are placed at more than one location of the vehicle. These distributed systems typically consist of forward and rear sensors. Forward (front) sensors, sometimes called crush-zone sensors, are usually located in the engine compartment while rear sensors are located in the passenger compartment.

Certain sensors in a distributed system are called discriminating sensors. Their task is to differentiate severe crashes from no-fire situations. They may be installed in a forward or rear lo-

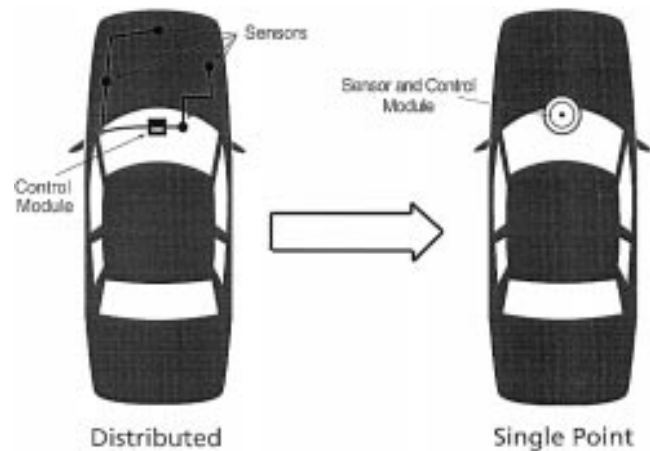


Fig. 7. Transition from distributed sensing systems to single-point sensing systems.

cation. Another type of sensor, arming sensor, is often located in the passenger compartment. The initiation of an air bag in a distributed sensing system requires the simultaneous closure of at least one discriminating sensor and an arming sensor. Arming sensors are used to prevent undesired deployment in faulty conditions when local impacts occur to forward sensors but the impacts are not sufficient to cause a significant slowdown of the vehicle.

Electrical contacts inside the crash sensors are bridged by resistors so that integrity of the firing and sensing loops can be monitored by circuit continuity without actually closing any sensor's contacts. To diagnose and monitor multiple sensors and to control triggering events in a sensing system, an electronic control unit (ECU) is typically included in a distributed system.

2) *Single-Point Sensing*: In a single-point system, a crash sensor is integrated with a conventional ECU into one single unit. To provide a secure, robust, and noninterfering environment, the location is typically in the passenger compartment. Fig. 7 illustrates the transition from a distributed system into a single-point system.

As pointed out in Section III, most mechanical sensors are speed-dependent and they function by detecting the speed change of a vehicle in collisions. On the other hand, electronic sensors are designed to differentiate crash events by variables beyond speed change. This specific distinction favors the use of electronic sensors in single-point sensing systems. However, mechanical sensors have also been found to perform satisfactorily on certain platforms in single-point configurations. These all-mechanical systems use mechanisms in place of electrical circuits, therefore eliminating the needs for electrical wiring and power supply [14], [19].

3) *Implementation Issues of Single-Point Sensing Concept*: Various crash types generate crash signals of distinct characteristics. Crashes under different conditions are sometimes referred to as hard or soft, depending on the "stiffness" of impact interface. A head-on crash into a rigid barrier is a hard crash, while an angular crash into a deformable obstacle is a soft one. The variations of crash types present considerable challenges to crash sensing design. The challenge is particularly amplified in the implementation of single-point sensing [44]–[48].

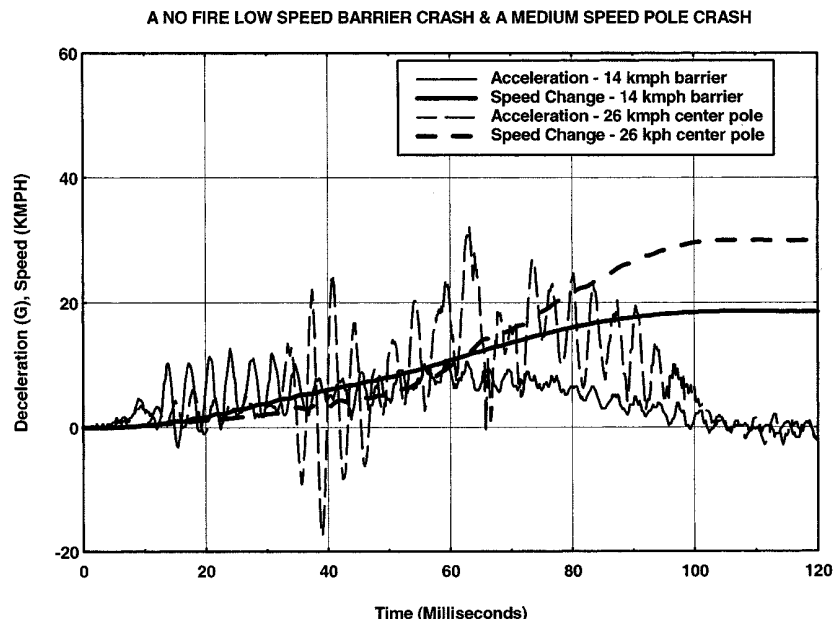


Fig. 8. Comparison of a low-speed impact barrier crash and a medium-speed pole crash.

When a single crash sensor is used in the passenger compartment, the sensor must recognize the crash signals transmitted to its location. Since hard and soft crashes present different pulse shapes and magnitudes, the problem of crash sensing becomes difficult in differentiating crashes near the threshold level when bag deployment is not needed. For instance, a crash sensor may fail to discriminate a medium-speed soft crash from a marginal nondeployment hard crash.

As an illustration of crash signals in the passenger compartment, Fig. 8 shows the acceleration pulses and the integrated (speed) curves of two crashes. The first crash is a low-speed impact barrier when no air bag deployment is needed while the second is a medium-speed pole crash requiring deployment. If a comparison is made only in the speed curves, it can be seen that the second crash is at a level below the first crash until 60 ms into the crash event.

If a speed-dependent sensor is used at this location, it may fail to detect the second crash in time. Therefore, the single-point sensor must extract other information in the acceleration signals to differentiate the two situations. For example, the acceleration signal of the second crash in the 30–40-ms window shows a higher degree of fluctuation and magnitude. An electronic sensor must use algorithms to derive such properties, such as jerk values, from the signal to be successful in crash discrimination.

Some design issues in single-point sensing lie in the unique characteristics of a vehicle platform, such as in an application for light-duty trucks [49]. It is common to have structural and mass variations as much as 40% within a truck platform. This creates significant differences in crash signals for various models at identical crash speeds. An additional difficulty of crash discrimination for trucks is the abuse environment, such as off-road vehicles, and add-on equipment such as snow plows, push bumpers, or winches. An auxiliary mechanical sensor placed in the crush zone can aid in the calibration of restraint system for nondeployment immunity. This proposed arrange-

ment is a good example of how different types of sensors can be used to supplement each other for a better design.

D. Side-Impact Sensing

The discussions up to this point have dealt primarily with crash sensors intended for frontal collisions. This section covers the topic of crash sensors for side impacts. Due to the distinct features of vehicle structure and collision dynamics, side impact characteristics are different from those in frontal collisions. These differences are reflected on the types of sensors suitable for side impact restraints.

Volvo, with its 1995 850 model, was the first automobile manufacturer to market side impact air bag systems as standard equipment [50]. BMWs were the first production cars with inflatable head protection systems (HPS) designed specifically to protect occupants' heads in side impacts [51], [52]. In current and upcoming years, more automobile companies are expected to offer side air bag systems. [53]–[56]

The functioning sequence of side air bags is much faster than in frontal impacts. For targeted crash conditions, such as a 48-km/h car-to-car impact, sensors need to trigger within 3–5 ms while side bags are designed to inflate within 7–15 ms. Several types of sensors have been proposed and developed for side-impact sensing, including mechanical switch, pressure, and acceleration. This section reviews a few examples and the associated design issues.

1) *Mechanical Crush Switch*: An example of a crush switch is the one used by the Volvo system, SIPSAB—side impact protection system bag. The sensor is installed on the side frame of the seat with the top facing toward the door. When a side impact causes the side door to deform inwards, the sensor reacts when the incoming blow occurs with a sufficient speed and impact force [57], [58].

One concern with crush switches is whether pre-existing dents or deformation will affect the sensitivity of the sensing

system. The other design issue with the crush concept is the placement strategy. A switch installed at one selected location is likely to miss localized impacts at other locations, such as a pole collision at a distance from the switch. If switches are spread over the side structure, measures must be taken to prevent misfiring in nondeployment conditions.

2) *Pressure Sensor*: A different concept for side-impact sensing, using pressure sensors, was described by Hartl *et al.* [12]. The pressure sensor is located in the interior of the door structure. The door interior functions as a closed chamber, which experiences a decrease in volume and an increase in pressure at the time of impact. When the pressure exceeds the threshold, a firing signal is given.

A design issue arises when the deformation to the door cavity comes from an offset or pole impact such that the volume change is limited. The challenge of using pressure sensors lies in the differentiation between such impacts and minor or low-speed vehicle-to-vehicle collisions. The proper pressure threshold can only be determined empirically. To prevent false signals from atmospheric pressure, the pressure sensor must measure the dynamic change of pressure variation, not a static increase. The dynamic response of the pressure sensor must be able to react to a pressure rise within a few milliseconds.

3) *Acceleration Sensor*: The concept of using accelerometer sensors is similar to that of employing electronic sensors for frontal air bag systems. Acceleration signals, measured at one or more locations of the vehicle, are processed by sensing algorithms and implemented in electronic circuits. If the properties of the signals meet the criteria set by the algorithms, a firing signal is generated [12]. A number of inventions have been claimed in the use of acceleration signals for side-impact sensing [59]–[61]. Sensing algorithms in these side-impact sensors involve the calibration of acceleration levels, fluctuation, velocity, and energy levels.

One interesting implementation [62] suggested using accelerometers mounted on opposite sides of a vehicle to supplement each other in detecting side impacts. The accelerometer mounted on the driver's side provides a discriminating signal in a driver-side impact while another accelerometer on the passenger side yields an arming signal. The roles of both sensors reverse if an impact occurs to the passenger side. In another example [63], a third accelerometer mounted near the center of a vehicle was added to the concept. The occurrence of a side impact is confirmed by a discriminating signal on either side and an arming signal from the center location or the opposite side. The calculation of a six-point moving average of acceleration is suggested as the threshold measure for the discriminating signal and a three-point moving average for the arming signal.

Sensors for side air bags have an extremely short detection period of 3–5 ms. For this reason, an integration routine in sensing algorithms may not be as significant as its physical representation in frontal collisions. Instead of taking the acceleration-integrated value literally as a velocity variable, it is more meaningful to assume that it is an indication of average acceleration during that period of time. Also, the placement of accelerometers and their relative location to the point of impact influences what can be reflected in the acceleration signals. The use of acceleration sensors requires careful quantification and verification by experiments.

4) *Design Approaches for Side-Impact Sensing*: To increase the reliability of a side-impact sensing system, two or more types of sensing methods may be combined. Candidate devices to be used in a combination strategy may include crush and acceleration sensors [64]. To determine proper timing of restraint deployment, occupant sensors and seat belt lock sensors may be involved [65].

Another potential sensor placement strategy may incorporate a proximity sensor on the exterior of the vehicle. The proximity sensor, a radar or ultrasonic type, can detect an object approaching and provide a preview signal for the impact sensor. Since the proximity sensor only provides an alert signal, it must be used in conjunction with other sensors to constitute a complete system.

As more vehicles are equipped with frontal and side restraints, the overall placement and functionality of various sensors will require increasing considerations. For a combined single-point sensing of frontal and side impacts, the actuation of side restraints can be disabled if a frontal crash condition is sensed [66]. The decision making in a multiple-restraint and an integrated sensing system may translate into complicated design requirements and placement strategies.

IV. ADVANCED AIR BAG SYSTEMS AND SENSING FUNCTIONS

With the functional requirements of smart air bags proposed for future products, the task of crash sensing has become more demanding and challenging. In this section, we will discuss the definitions of smart air bags and the resultant implications for crash sensing.

A. Definition of Smart Air Bags

In recent years, there have been a number of crashes involving occupant fatalities and injuries due to air bag deployment. In the pursuit of solutions for these undesired side effects, the terminology of “smart air bag systems” has been adopted for the next generation of restraint systems. At times, they are referred to as advanced air bag systems. Before proceeding further on discussions of crash sensing, a clarification of what “smart air bag systems” imply is in order.

1) *Proposed Rulemaking by NHTSA*: On June 9, 1998, the Transportation Equity Act for the 21st century (TEA-21) was signed into law. In addition to general National Highway Traffic Safety Administration (NHTSA) policy direction, TEA-21 mandates a specific rulemaking schedule regarding advanced airbags. A press release on Sept. 14, 1998 gave more details on the proposed rule. Some selected excerpts are given here.

“The proposal by the department’s NHTSA would require additional air bag system performance tests for passenger cars and light trucks in order to provide maximum protection for properly seated adults and reduced risks for infants, young children and adults who get too close to inflating air bags. ...”

The proposal is in NHTSA’s Docket 98-4405. For information about air bags and related rulemakings, visit the NHTSA web site at <http://www.nhtsa.dot.gov> and select “air bags” under “popular information.”

2) *Advanced Air Bag Technology Assessment by JPL*: Under an agreement between NHTSA and National Aeronautics and Space Administration (NASA), the Jet Propulsion Laboratory (JPL) conducted an advanced air bag technology assessment [67]. JPL attributed the cause of air bag injury to the design of current air bag systems and the variability of the crash process. JPL envisions that air bags can be safer and more protective with improvements in progress and in years to come, including the following.

- 1) Depowering, i.e., reducing the inflation rate and pressure, was permitted in 1997 by an amendment to FMVSS 208. Depowering, introduced in model year 1998, will reduce the risk to small-stature drivers, out-of-position drivers and front-seat passengers.
- 2) Some promising technologies may be available by model year 2001, such as improved crash sensors, belt use sensors, and seat position sensors. Other potential improvements include belt spool-out sensors and static proximity sensors to provide improved occupant position determination. Improvements in response include automatic suppression to prevent inflation, two-stage inflators, compartmented bags, variable venting and advanced safety belts. The last group of improvements can provide more tailored response, especially for out-of-position situations.
- 3) By model year 2003, occupant weight and position sensors should be available to be used with sensors and response capabilities previously developed.

3) *General Comments on Advanced Restraints*: The author suggests a broad definition of smart air bag systems as follows:

A system that deploys air bags at a level according to the conditions of the crashes, the vehicle, and the occupants to minimize risks and to maximize occupant protection benefits.

Such a definition can be extended similarly for smart restraint systems:

A system that deploys safety restraint devices only to the extent that is needed according to the conditions of the crashes, the vehicle, and the occupants to minimize risks and to maximize benefits.

The latter definition is expanded to include all sorts of occupant protection devices, such as seat belts, pre-tensioners, inflatable devices, and head restraints.

4) *Performance Requirements of Smart Air Bags*: Since smart air bags are intended to provide improvements over current products, it is necessary to first review the types of problems associated with current systems. They can be described as follows.

- a) Premature bag deployment causes unnecessary injuries in nondeployment situations, a consequence of the sensing system failing to discriminate accident situations properly.
- b) Late-deploying bags cause injuries or fatalities. In other words, the timing of deployment is improper.
- c) Child fatalities occur when children are situated or improperly restrained in the path of a deploying bag.

TABLE IV
CURRENT PROBLEMS AND CORRECTIVE MEASURES IN SMART AIR BAG SYSTEMS

Source of Problems	Corrective Measures
Discrimination of crash conditions not robust	Change sensor types; Enhance sensing algorithms; Adjust sensor placement strategies
Deployment Timing inappropriate	Enhance sensor performance; Examine sensing placement strategies; Add timing features into sensing algorithms
Use of restraints improper	Adopting multiple levels of restraints; Make selection of restraint devices flexible; Improve ECU to identify proper restraint levels
Recognition of vehicle interior unavailable	Add occupant sensing capabilities for child-seat and out-of-position situations

- d) Out-of-position occupants seated too close to the modules housing of the air bags sustain injuries from the deployment. Situations (c) and (d) result partially from the sensing system failing to recognize conditions in the vehicle interior.

Corresponding to the problems associated with current air bags, corrective measures to improve their performance are listed in Table IV:

Based on the discussions above, one may construct a smart restraint system by assembling the following elements.

- a) *Smart Sensor*:

The sensor must be intelligent enough to differentiate crash types and decide the proper timing of deployment.

- b) *Occupant Sensors*:

The sensing system must possess the capability to identify occupant positions and the status of vehicle interior.

- c) *Flexible Restraints*:

Different levels of restraints must be available to meet various deployment conditions, including choice of restraints, e.g., belts or bags, and degree of deployment, such as dual-stage or multiple-staged inflators.

- d) *Control Unit*:

The control unit must govern the performance of various sensors and command the use of flexible restraints according to the sensor inputs.

- e) *Communication Network*:

A network connecting all elements within the system must provide efficient and reliable communication to facilitate data exchange and system control.

B. Crash Sensing for Smart Air Bags Systems

Sensing systems in conventional systems are designed to differentiate between deployment and nondeployment situations. Smart systems perform beyond that level and must recognize (a) crash situations, and (b) vehicle interior conditions. The ability

to capture these two types of information allows the smart systems to adjust (a) the timing of deployment, and (b) the level of deployment accordingly.

1) *Occupant Sensing*: Occupant sensing is one of the key technologies required in smart air bags. Essentially, its goal is to recognize the conditions within the vehicle interior that may affect the performance of restraint systems. Occupant sensing can help in situations such as rear facing child seats in the front passenger seat and out-of-position occupants, or deployment suppression in empty seats.

Several types of technologies have been suggested for occupant sensing [68]. Occupant weight can be sensed by some means of determining seat deformation [69]. The distance between an occupant and an air bag module can be measured by ultrasonic or infrared sensors [70]. Another approach uses a capacitive detector that measures the change caused by the presence of an occupant [71]. The variation of electric field caused by the presence of occupants can also be used to obtain desired information about an occupant [72].

In most cases, several types of sensors are likely to be combined to produce a complete occupant sensing system. For example, some proposed systems use ultrasonic along with infrared sensors to identify vehicle interior patterns. Others suggest the use of capacitance or infrared sensors on the dashboard in conjunction with weight sensors in seat cushions. In addition to ultrasonic, microwave, or optical technologies, occupant sensing may also rely on seatbelt spool out and seat position sensors to provide inputs to the electronic controller.

2) *Integrated Sensing Systems*: The role of crash sensing has expanded due to the demand of an advanced restraint system. The objectives of the sensing system are not limited to just crash detection and discrimination, as provided by traditional crash sensors. At various stages of a crash, different parts work together in an integrated system to achieve a high level of safety performance.

An integrated sensing system includes the following four functional stages [73].

a) *Anticipation*:

This first stage involves the pre-impact estimation of eminent collision scenarios. For example, the information coming from radar or some type of proximity sensor can enhance the timeliness of sensor triggering [74], [75].

b) *Confirmation and Discrimination*:

As a collision occurs, crash sensors are engaged in the process of confirming or discriminating the measured signals. Sensors are required to identify the types and severity of crashes so that a proper control command can be issued for the next stage.

c) *Deployment Control*:

The functions of this stage are twofold. On one hand, the control unit receives inputs from various sensors, such as crash discrimination and occupant position sensors, to establish conditions about the crash and the vehicle. On the other hand, the control unit commands the type of restraint, such as a pre-tensioner or an air bag, and the degree of deployment, as in a multiple-stage inflator.

d) *Post-Impact Handling*:

This last stage deals with tasks to mitigate the consequences of an accident. For example, to increase the speed with which first responders react to the report of an accident, several manufacturers have begun providing communication services that utilize global positioning systems and wireless communication to send an SOS signal when air bags are deployed.

3) *System Electronics*: As a result of the implementation of sophisticated sensing systems, and an increase in the number of restraint units and the types of sensors required, the network and associated electronics controlling the devices become more complex as well. In this new environment, the ECU may need to communicate with or respond to:

Input:

Seat belt buckle switch, seat occupancy, rearward facing child seat, out-of-position status, occupant weight, inflator pressure and temperature, side-impact sensing status, device for diagnostics and pre-crash/early-crash sensing,

Output:

Front and side inflators, belt pre-tensioner, knee bolster, warning lamp, fuel cutoff switch, door lock, emergency communication.

The limitation of ECU growth at a single location requires a modular design and a distributed electronic system [76]. With standardization, modular design should reduce the overall system development cycle and costs. A distributed system may include remote firing circuitry, which allows squib activation by a communication bus command, and intelligent nodes, which are stand-alone subsystems connected by a communication channel. Various forms of modular design with different degrees of intelligence distribution are allocated at selected locations on the electronic network.

The increased complexity of the restraint system also raises the requirements on the in-vehicle network [77]. The major requirements of a reliable and affordable network may include the following.

- a) *Safety*: such as fault tolerance and reliable and high-speed communication.
- b) *Economy*: simple circuitry for power extraction, electromagnetic compatibility to allow use of unshielded wires, or power and data transmission on the same wires.
- c) *Flexibility*: free network topology, wide-range number of nodes, future extensions.

C. *Rollover Sensing*

One area that has not been elaborated, but may become an integrated part of a complete restraint system is rollover sensing and protection. Manufacturers are offering tubular and window-curtain types of air bags for side impact protection [51]–[56]. Even though these systems are mainly designed for side collisions, they may also provide protection in rollover accidents. With these devices already in place, it provides an incentive to add rollover sensing to passenger vehicles. The realization will depend on how quickly that the automobile and the public are ready to accept such standard or optional equipment at a reasonable cost.

Warning systems for vehicle rollover were first proposed in 1970s and 1980s mainly for tractor-trailer combinations [78]–[81]. The development and installation of safety devices on light-duty vehicles only began to emerge in recent years [82], [83]. For rollover protection, sensors function in two stages: 1) detection and warning and 2) protection device deployment. Most of the existing literature emphasizes on the first stage. Especially for the heavy truck and tractor-trailer platforms, the rollover event initiates a considerable period of time ahead of the eventual turning-over of the vehicle. Therefore, warning systems may allow the driver to take actions to avoid such accidents. There is generally less time available for avoiding a rollover in the case of passenger cars once the vehicle is already entering the rollover mode. Thus, the utilization of rollover sensors for passenger cars is more applicable for the second stage, i.e., restraint deployment for occupant protection.

There have been a number of different sensors proposed or developed for rollover detection, such as: 1) optical-electrical tilt sensor [78]; 2) ultrasonic sensor [79]; 3) mechanical tilt sensor [80]; and 4) strain sensor [81]. An integrated rollover sensing system may include two or more kinds of sensing devices. For example, some systems [82]–[84] used a combination of several sensor types, including force sensor, pressure sensor, and accelerometer. Steiner *et al.* presented a concept of using acceleration and yaw rate sensors in rollover detection [85].

D. Integration of Occupant Restraint Systems

In recent years, there have been an increasing number of studies that evaluate the effectiveness of air bags and seat belts. Studies were conducted to investigate the possibility of optimizing restraint forces with a combination of belts and air bags. Improved and adjusted belt force limiters and the adjustable venting concept, or pressure-controlled air bags, are proposed for smart restraints [86]–[88]. Working in tandem, these systems may adjust the initial occupant-restraint interaction.

Other approaches have been suggested to improve the system performance of safety restraints. One design [89], for example, proposed the development of an air bag-integrated steering wheel, in order to optimize occupant protection when balanced against out-of-position risks. Another area of restraint system design focused on the adaptability of an air bag module. Pyrotechnically actuated venting offers an innovative method for regulating air bag inflation energy [90]. The recent introduction of inflatable tubular cushions in BMW models was another illustration of expanding use of air bag in an integrated restraint system [54]. When the tubular bag is inflated, the diameter of the tube increases significantly and its length decreases significantly, due to the orientation of the fibers comprising the braided tube. The contracting tube pretensions the seatbelt system by pulling any slack out of the seat belt systems. Occupant restraints are also expanded to include protection in rear impacts. For example, an automatically adjusting head restraint system was proposed and developed to serve as a passive head restraint in the event of a rearward impact [91], [92].

What can be inferred from the studies or products mentioned above is that research and development efforts for occupant

restraint systems is moving in the direction of a “complete” system design. Design for a complete system not only considers the necessary components but also utilizes the full advantages of each component. In an advanced or integrated system, the individual components must possess specific characteristics in order to complement each other and to achieve optimal performance.

The design of occupant protection can be viewed as an “energy management” problem [93], [94]. In the course of a collision, the restraint system responds to “manage” the kinetic energy of the occupant. The objective is to dissipate this energy as smoothly as possible so that occupant injuries can be avoided or mitigated. The forces on the occupant should be low and the excursion of the occupant limited. Restraint force optimization seeks a balance between restraint force and occupant excursion.

V. CONCLUDING REMARKS

The following observations can be made regarding the developments in crash sensing during the last decade.

- 1) Crash sensing technologies have made tremendous progresses, with restraint devices effectively mitigating consequences of vehicle accidents.
- 2) Electronic sensors are playing an increasing role and taking a greater market share from the traditional speed-sensing sensors.
- 3) New challenges lie ahead for crash sensing systems, with new applications and innovations in safety devices for occupant restraint systems.
- 4) Future developments in crash sensing will require the integration of various technologies to achieve an optimal level of performance.

In order to forecast the directions of future developments of crash sensing technologies, it is necessary to understand the trends of air bags and occupant restraint evolution. It is already apparent that smart air bags will require the integration of innovative improvements in seat belts, inflators, and an assortment of sensing devices. What will likely to follow is that air bags become a part of a “friendly vehicle interior”. The goal of a truly integrated system is to smartly manage the transition of vehicle and occupant energies in accidents. A proper level of restraint is applied so that an optimal level of damage mitigation is achieved. Within the scope of this definition, sensing devices will serve the monitoring, diagnosis, and control functions in an integrated system. The continual demand for better ways to ensure occupant safety will stimulate further progresses in the design of occupant restraint systems. Along with this trend, crash-sensing technologies will remain a challenging area for years ahead.

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